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EFFICIENT AND EFFECTIVE RESIDENTIAL AIR HANDLING DEVICES

Final Report

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TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

ABSTRACT

This study examined the efficiencies of residential ventilation and furnace fans. The scope included a detailed review of motor and motor control technology, fan design issues, and an international search of motor/fan combinations of conventional and higher-efficiency. It was found that current residential air handlers are often ten times less efficient than their larger commercial counterparts. Cost effectiveness considerations of ventilation and furnace fans (the most energy intensive applications), showed that dramatic improvements in efficiency are justifiable.

KEY WORDS

Residential ventilation; furnace fans; efficiency; reduction in energy use; motors; speed controls; and fan design.

ACKNOWLEDGEMENT

We sincerely appreciate the strong interest of Jim White in this subject and his encouragement to produce a significant document. Appreciation for their continued cooperation is extended to Doug Geddes (Geddes Enterprises), Brian Woods (Ontario Hydro Research), and Dara Bowser (Bowser Technical). The effort on report production by Sandra Lester of Allen Associates is gratefully acknowledged.

EXECUTIVE SUMMARY

Small air handling devices in homes are pervasive, ranging from furnace blowers and ventilation fans to hair dryers and computer fans. Their efficiencies are dramatically low, ranging from 1% to 10%, whereas larger, engineered air handlers range from 60% to 80% efficient.

Many of the small electric air moving devices have short run times, accumulating very small relative amounts of energy consumption. On the other hand, some of the larger fans, with input power ranging from 50 W to more than 1000 W, may have significant to continuous run times. With increasing attention being paid to indoor air quality, continuous ventilation and filtration via recirculation are increasingly becoming the norm.

A typical house with mechanical ventilation may experience 1,500,000 m^3 of air exchange annually, resulting in a 5000 kWh (1500 kWh with **70%** heat recovery) space heating requirement. The space conditioning system may move another 2,000,000 to 13,000,000 m^3 annually. The corresponding fan energy ranges from 1000 kWh to 8000 kWh, for an annual cost of $80.00 to $360.00 (at $0.08/kWh), becoming non-trivial at higher levels.

Current residential air handling devices are almost an order of magnitude less efficient than their larger commercial and industrial counterparts. Furnace fan efficiencies are in the order of 20% but, with poor furnace cabinet air flow design, the efficiency in terms of air moving load external to the furnace reduces the efficiency to 7%. Individual exhausters are typically less than 2% efficient. The spread between poor and best available equipment is in the order of ten to one.

The potential for energy efficiency improvements of small air handlers is clearly vast. Examination of the technology revealed that, in some cases, motors with peak efficiencies lower than 20% can be replaced with ones whose peak efficiencies are over 70% at cost premiums from $20 to $100. Similarly, improvements in impeller/housing combinations can be dramatic, if designed from fundamentals. Five-fold improvements seem indicated from currently available and emerging equipment. Optimized variable speed drives for AC induction motors, and DC electronically-commutated motors, can allow for high efficiency in part load and variable flow conditions, significantly reducing not only motor input power but time-integrated energy use.

Tables I and II illustrate improvements for a typical furnace blower application. The industry seemed unaware of the magnitude of the problem, until contacted as a part of this project, and may require support and/or inducements to rapidly bring better equipment to the market place.

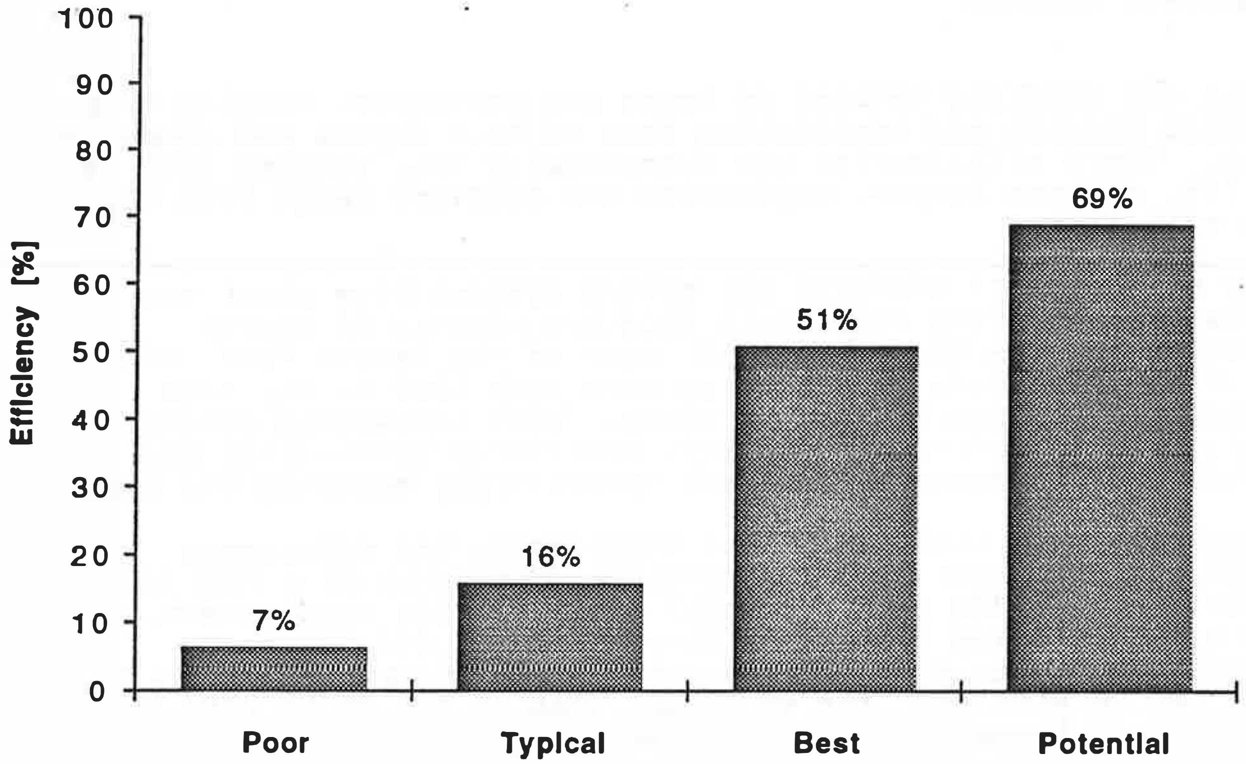

Table I Efficiency Improvements for Furnace Fan.

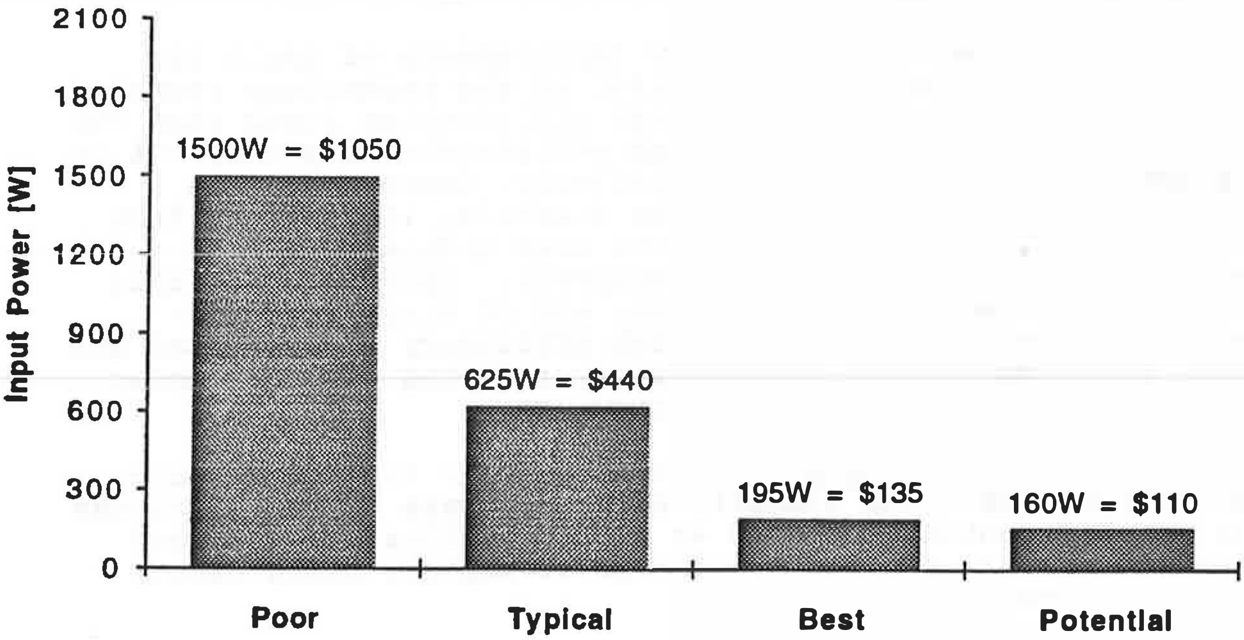

Table II Input Power and Annual Energy Cost for a Continuously Operating Furnace Fan (electrical cost = $0.08 kWh; air moving load = 100W).

RESUME

Les petits dispositifs de ventilation sont de plus en plus répandus dans les habitations. Allant du ventilateur de générateur de chaleur et des ventilateurs-extracteurs au sèche-cheveux et au ventilateur d'ordinateur, ces appareils ont un rendement qui varie entre 1 p. 100 et 10 p. 100. C'est là une piètre performance quand on sait que les gros appareils offrent un rendement de l'ordre de 60 à 80 p. 100.

Bon nombre de petits dispositifs de ventilation ne fonctionnent habituellement pas longtemps, ce qui entraîne une très faible consommation relative d'énergie. Par contre, certains ventilateurs imposants, dont la puissance d'entrée oscille entre 50 W et plus de 1 000 W, sont appelés à fonctionner longtemps, sinon continuellement. Vu l'attention accrue accordée à la qualité de l'air intérieur, la ventilation continue et la filtration par recirculation deviennent de plus en plus la norme.

Une installation de ventilation mécanique typique peut réaliser un échange d'air annuel de 1 500 000 m³, ce qui se traduit, pour l'habitation, par une charge de chauffage de 5 000 kWh (1 500 kWh si l'installation récupère la chaleur à 70 p. 100). En outre, une installation de climatisation peut déplacer chaque année entre 2 000 000 et 13 000 000 m³ d'air. L'énergie correspondante pour le ventilateur varie entre 1 000 et 8 000 kWh, soit un coût annuel se situant entre 80,00 $ et 360,00 $ (à 0,08 $/kWh), des chiffres qui deviennent significatifs aux niveaux supérieurs.

Les dispositifs de ventilation actuellement en usage dans les habitations sont moins efficaces de près d'un ordre de grandeur que les grosses installations utilisées dans les établissements commerciaux ou industriels. Le rendement des ventilateurs de générateur de chaleur est habituellement de l'ordre de 20 p. 100, mais lorsque le circuit d'air interne de l'appareil est mal conçu, ce rendement peut être réduit à 7 p. 100 pour ce qui est du mouvement d'air à l'extérieur du générateur d'air chaud. Les ventilateurs-extracteurs individuels affichent habituellement une efficacité inférieure à 2 p. 100. Le rapport entre les appareils de grande qualité et de piètre qualité est de l'ordre de 10 à 1.

Le potentiel d'augmentation de l'efficacité énergétique des petits dispositifs de ventilation est donc considérable. L'examen de la technologie révèle que, dans certains cas, les moteurs dont l'efficacité optimale est inférieure à 20 p. 100 peuvent être remplacés par des moteurs offrant une efficacité optimale dépassant 70 p. 100 pour un coût additionnel variant entre 20 et 100 $. De même, les améliorations apportées au rotor et au boîtier peuvent faire toute la différence si la conception est complètement repensée. Les dispositifs actuels et nouveaux pourraient en effet être améliorés de cinq fois. Les moteurs c.a. à induction à vitesse variable optimalisés et les moteurs c.c. à commutation électronique peuvent améliorer le rendement dans des conditions de charge partielle et de circulation variable, réduisant ainsi de beaucoup non seulement la puissance d'entrée du moteur, mais aussi l'utilisation total d'énergie. Les Tableaux I et II illustrent les améliorations obtenues pour un ventilateur de générateur d'air chaud. Les membres de l'industrie semblaient ignorer l'ampleur du problème jusqu'à ce que les auteurs communiquent avec eux aux fins de la présente étude. Si l'on veut que l'industrie produise rapidement de meilleurs appareils, il faudra probablement appuyer leurs efforts et proposer des mesures incitatives.

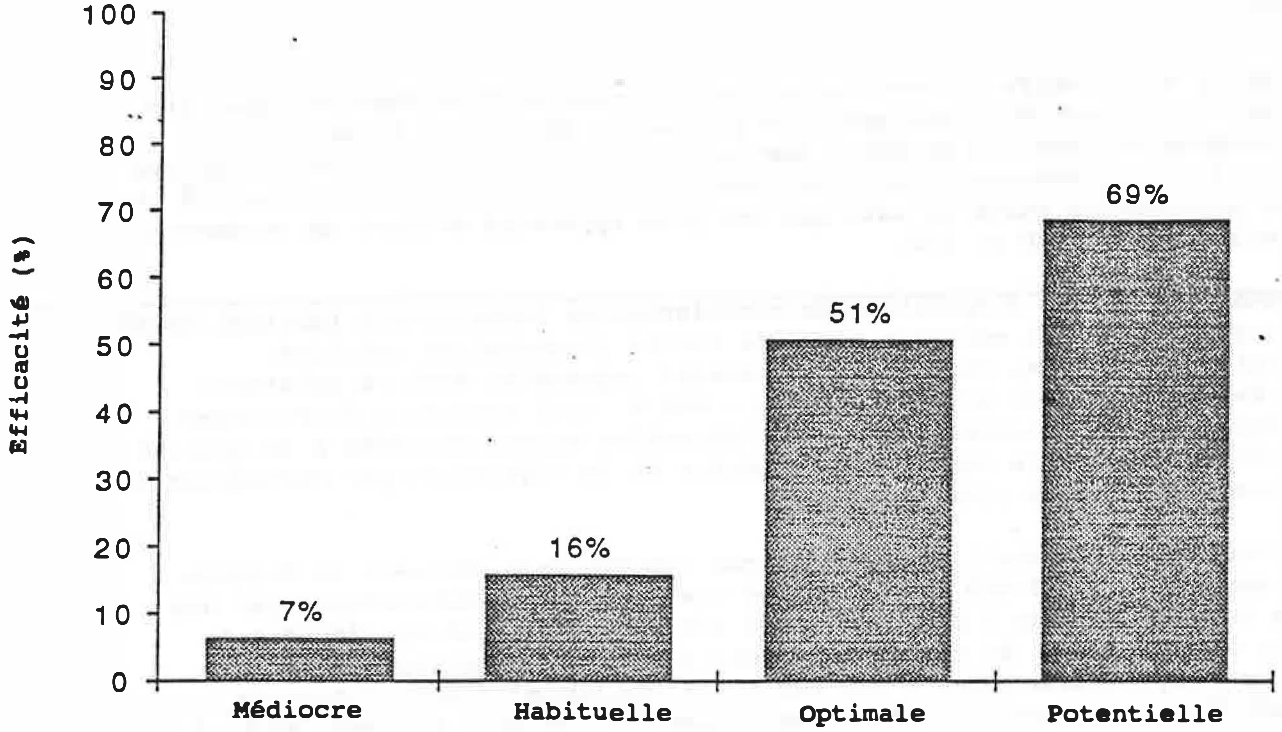

Tableau I **Amélioration de l'efficacité d'un ventilateur de générateur de chaleur**

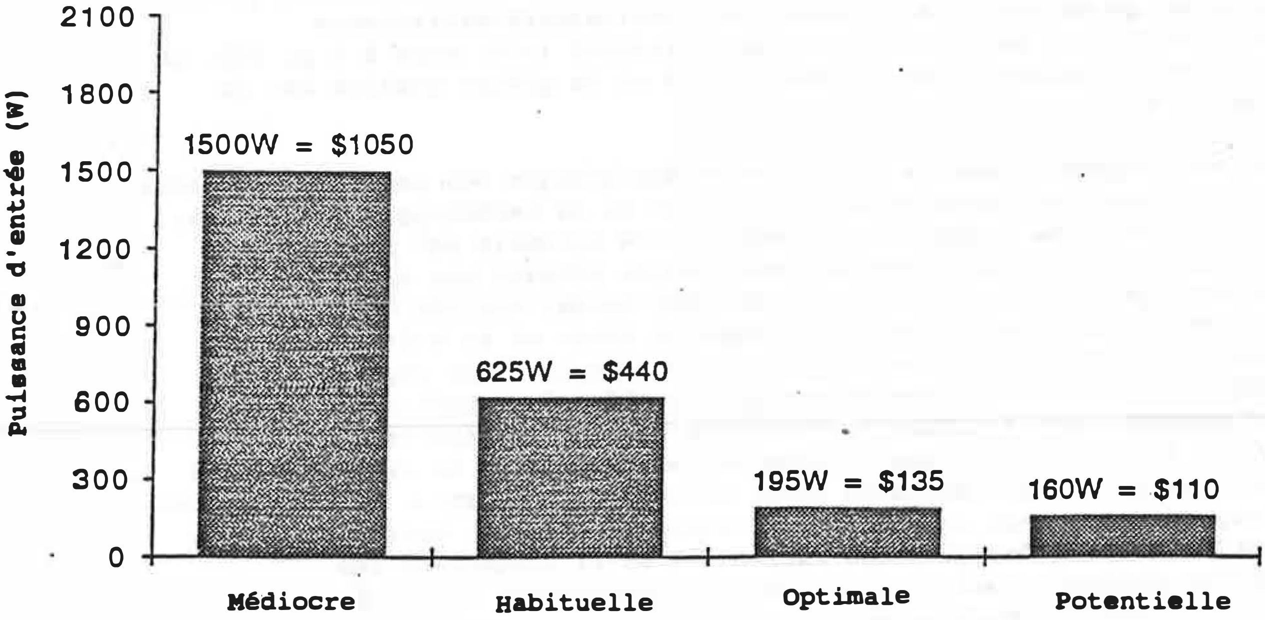

Tableau II **Puissance d'entrée et coût énergétique annuel pour un ventilateur de générateur d'air chaud fonctionnant continuellement (prix de l'électricité = 0,08 $/kWh; charge de circulation d'air = 100 W)**

TERMINOLOGY

To avoid confusion and simplify the wording used in the report, the following terms have been defined.

ASD	- adjustable speed drive.
Air Handler	- complete motor/fan set; includes all controls, motor, impeller and housing.
Blower	- fan in which the direction of air flow is changed by 90°; typically centrifugal impellers inside scroll housing - common air handling device for furnaces and ventilation systems.
Distribution	- ductwork attached to a packaged piece of system equipment for purposes of delivering air to, or returning it from, various parts of the house.
Dynamic Head	- the extra pressure created when air velocity is reduced to zero.
Efficiency	- the ratio of the work output [J] to the input energy [J] or the power output [W], to the power input [W].
Fan	- air moving component, usually consisting of an impeller and housing, but sometimes impeller only, e.g. ceiling fan.
Fan Efficiency	- ratio of aerodynamic power [W] (airflow x pressure) to motor output [W] required (shaft power).
Motor Efficiency	- ratio of shaft power [W] to input power [W] of a motor.
Motor/Fan Set	- motor, impeller, housing and drive (if any).
Motor/Fan Set Efficiency	- (ε_{mf}) = $\varepsilon_m \times \varepsilon_f$.

TERMINOLOGY (Cont.)

Power Factor	- ratio of active current to the total current. - the total current is the vector sum of the active component (work output related) and the reactive component (magnetic field related).
Rotor	- rotating part of the motor.
Rpm	- revolutions per minute.
Static Efficiency	- ratio of power required to move a volume of air against an external static pressure to the impeller shaft power.
Static Pressure	- pressure of air at rest (i.e. total pressure less dynamic head).
Stator (motor)	- stationary part of the motor, but may have rotating magnetic field.
Stator (fan)	- stationary correcting vanes in fans.
Total Air Handler Efficiency	- ratio of the aerodynamic power [W] to total electrical input power [W] to the air handler. Usually lower than ε_{mf} to account for electrical consumption of additional electrical components, e.g. controls.
Total Pressure Difference	- sum of velocity pressure difference and static pressure difference.

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1.0 INTRODUCTION

1.1 Context

The use of mechanical air moving equipment in Canadian housing has increased from virtual non-existence before the 1950's to become the largest electrical appliance load. In many houses the annual electrical use for blowers exceeds all lighting and appliance loads combined. For many houses the cost of that usage is in the range of hundreds of dollars per annum.

Initial appraisal of air handling equipment and systems reveals sizable inefficiencies. Furnace blowers, for example, may deliver air at 1/5 the aerodynamic efficiency (and worse) of their larger commercial cousins. Worse still, equipment oversizing, air losses, and high static pressure requirements result in blower loads far higher than necessary. Other air movers, (such as rangehood fans, bathroom exhausters, and heat recovery ventilators) are no better. Generally they are worse.

The energy inefficiencies should be viewed in the context of their air handling performance and how well their purposes are served. Fundamentally, air moving in the household is for removing contaminants, distributing conditioned air, or regulating outside air intake. Too often, installed systems fail to effectively achieve their function and may even deteriorate comfort and air quality. For example, the clothes dryer blower exhausts moisture, but in doing so may draw in flue gases from the hot water heater. Recirculating furnace blowers often are drafty when the heating is not on.

We may therefore ascribe some importance to an evaluation of the potential for improving residential ventilation equipment and practices, both from the standpoint of energy efficiency and operational effectiveness. This study examines the current performance of residential air handling systems, the best technology available, and the potential for improvement by the end of the millennium.

1.2 Historical Background

Pre-industrial ventilation practices were an integral feature of architecture. Smoke holes and stacks adorned the peaks of virtually all housing forms, the object being to exhaust noxious combustion gases of the cooking and heating fires. In cold climates, means were devised for introducing makeup air without freezing the occupants, generally by channelling the air beneath the occupied zone to the fire pit and sealing all else but the smoke hole. Such practices were not always ideal, and no doubt contaminated lungs and the atmosphere, but were at least sustainable, for most of the population densities and life expectancies up until the modern era.

Some quite elaborate techniques of air handling were employed by early civilizations. Middle-Eastern air cooling strategies, which employ wind scoops and convective night-cooled towers, have been exploited for thousands of years. The Romans built spas that employed circulation of combustion gases through floors and walls, to achieve radiant heating.

Northern Europeans, in response to climate demands, built fireplaces and masonry heaters along with operable windows, to respond to summer and winter ventilation needs. Cold and smoke must have been standard fare.

The Age of Enlightenment ushered in many inventions related to air handling. Benjamin Franklin's cast-iron woodstove, with combustion air feed, proved to be the precursor of many of today's heating appliances. Count Rumford, his contemporary, reformed the fireplace for both better draw and heat output.

The first mechanical air movers were steam-driven fans for venting coal mines, but it would take until the second half of the 20th Century for forced air equipment to be extensively used in housing. The Victorians relied mainly on elaborate, sometimes ingenious, means of heating and venting buildings with natural convection. Gravity systems prevailed until the 50's, except for summer cooling fans.

In North America, forced-air furnaces rapidly took over the housing market, whereas hydronic distribution prevailed in Europe and the Maritimes (it would be interesting to conjecture why). In the 1960's, more and more household mechanical ventilating products poured onto the market - range hoods, bathroom fans, clothes dryers, and air conditioners. By the 1970's, the modern household was literally humming. Environmentalism and OPEC gave cause for re-evaluating household energy use. Interest spread in reducing heating bills by insulating, weatherizing, heat recovery ventilation, improving furnace efficiency, and employing renewable energy. The Canadian government championed technological change through such programs as CHIP (weatherization and insulating retrofit subsidy), COSP (subsidy for replacement of oil furnaces with alternatives) and SEEH Program (widescale demonstration of R2000 Standard new construction). Such rapid and politically-charged development led to a fractious process of adaptation. Central to many issues (that are still in debate today) is the impact of mechanical ventilation.

Most of the concerns regarding ventilation pertain to occupant health and safety, energy, and moisture damage. Without elaborating on the many issues and developments that are currently under examination across Canada, indeed around the world, it is sufficient to say that much is up in the air.

Despite a great deal of attention paid to mechanical air movers, not much regard has been given to the effectiveness and energy consumption of blowers. This report, then, is an important component of efforts to advance the art and practice of ventilation.

2.0 APPROACH

Consumption of air handling energy is a function of the time-averaged work required to move the air and the efficiency with which the air handler does this work. The effectiveness and efficiency of ventilation devices must be examined with a systems approach. Systems issues are discussed in the next section but are not dealt with in any detail. That is reserved for later projects.

Large opportunities for energy savings may be afforded by air moving load reduction, and the nature of the load determines the technology choice and the effectiveness. However, the efficiency of the air handling technology can, to some extent, be examined independently of air handling requirements. It is because the existing motor/fan sets are so very inefficient that this focus is justified.

Air handling technology, in terms of fans, motors, and controls will be described in some detail in this report. The various types of applications from high pressure furnace exhaust blowers to free air ceiling fans will be examined. An overview of design parameters is presented and the defining theoretical and practical limits of performance are presented.

To provide the required answers, a number of information gathering activities were undertaken. Reference materials, obtained from the collected literature of the team members and the project manager, were augmented by an international information search using the National Research Council's Canadian Institute for Scientific and Technical Information (CISTI) Literature Search of various databases. Product literature, both domestic and international, was assembled from manufacturers of motors, fans, and combined units, in addition to searching our own product files.

Using this information, more optimum impeller/housing combinations, motors, and controls were identified, to yield possible improvements in air handling performance. These technology concepts are compared with commercially available equipment. Reasons for discrepancies in performance are suggested.

The residential energy use for ventilation and space conditioning, assuming current practice and equipment, is presented for typical residential installations. Energy savings are quantified, for several levels of air handler efficiency improvement, ranging from the best current available equipment to projected economic potentials. The effect of control characteristics and operation by occupant is demonstrated and discussed.

The barriers to market penetration of new technologies are discussed in terms of market structure, limited access to capital, aversion to downtime and innovation, cost of testing programs, product pricing sensitivity and lack of incentives.

For the industry to move towards higher efficiency equipment, methods of performance evaluation, in terms of testing and labelling for energy consumption, must be developed. Existing standards are examined, both domestic and international, to see how fan energy is handled. Methodologies for seasonal energy ratings of ventilation and space conditioning air handlers are suggested. The role of the Ontario Energy Efficiency Act, and its eventual Federal counterpart, are discussed.

The necessary technical information transfer, training, R and D and incentives to accompany mandating energy performance are also identified.

3.0 RESIDENTIAL AIR HANDLING ISSUES

3.1 Overview

Before an assessment of the efficiency and effectiveness of residential air moving equipment is undertaken, it is important to consider the requirements placed on ventilation systems and components. Both the application and the context determine the characteristics and performance of air handlers.

Appropriate design must consider a host of factors including:

1. Power and energy demands;
2. Physical size;
3. Noise;
4. Location;
5. Attached components;
6. Volume flow rates;
7. Pressure regimes;
8. Health and safety;
9. Longevity;
10. Controllability; and
11. Condition of the air or gases.

Economics and industrial practices will then constrain the optimal performance to be expected. Although not the purpose of this investigation, the overall system performance should be recognized as a more fundamental concern.

The next sections discuss the significance of what air movers are connected to, and what they are supposed to be achieving. Future fan design requirements may substantially change, as a result of system improvements and modified practices. Sizing of both fans and motors should go down significantly, as flow rates and pressure drops are optimized, then provided with more efficient and effective fans and motors. As well, the significance of aerodynamic efficiencies should be placed in the context of the overall utility of our ventilation systems.

3.2 Applications

A partial listing of household air moving equipment will help to illustrate the diversity of requirements and extent of use.

1. Furnace blower
2. Bathroom exhaust fan
3. Rangehood exhauster
4. Radon mitigation blowers
5. Heat recovery ventilator
6. Ceiling and other cooling fans
7. Window air conditioner
8. Sun space exhausters
9. Induced-draft blower on combustion equipment
10. Heat pump or air conditioning unit fan
11. Clothes dryer
12. Dehumidifier
13. Air purifier
14. Convection oven
15. Vacuum cleaner
16. Attic fans
17. Hair dryer

An analysis of all of these devices is beyond the scope of this study. We will be concentrating on components which correspond to those that use both higher power motors and significant run times, as identified below. Lessons learned here may then be applied, as appropriate, to other devices and systems.

The list, nevertheless, reveals that air moving constitutes an extensive use of electricity in the home, with widely ranging operating characteristics.

Efficiency and effectiveness improvements must be kept in context. A hair dryer loses nothing through inefficiency since its motor losses merely contribute to electric resistance heating. It needn't be extremely quiet, but must be very robust. On the other hand, a room fan for cooling should be quiet indeed, and contribute as little heat gain as possible. Each application has a unique set of design parameters.

3.3 Energy Considerations

The annual electrical consumption of an air mover is a product of its flowrate times the total head, divided by aerodynamic efficiency, for each speed setting, integrated over time. Efficiency values should be viewed in relative terms, taking into account the overall impact. Infrequently operated devices, even with high aerodynamic loads (eg. a vacuum cleaner), need not be anywhere as efficient as a more frequently-run air mover of low load (eg. a continuous exhaust fan).

Table 3.1 gives typical ranges of hours of air handling operation, power draw, and annual energy consumption for the most energy intensive devices used in housing.

Other devices in the home use significantly less annual energy. For this reason, the focus of this report is on residential heating, ventilating, and air conditioning equipment. Forced-air heating and cooling equipment, as well as ventilation devices intended for continuous air change, are the most significant aerodynamic energy requirements of the household. This is not to suggest that other air moving equipment should not be scrutinized for their potential efficiency and effectiveness improvements. Collectively, their energy usage is significant and the economies of efficiency improvement may be favourable in a larger set than this study surveys.

3.4 Overall System Efficiencies

Furnace blowers are intended to promote comfort through uniform temperature distribution and to induce high heat transfer rates from heating or cooling elements. As secondary functions, they may be used to distribute outside air, remove contaminants through filters, and alter moisture content. The energy required to perform these tasks is beyond simple mass flow and pressure drop considerations.

Air Handling Device	Operation (hours)	Power (Watts)	Annual Energy (kWh)
Furnace Blower	2000-8760	400-1000	800-8800
Heat Pump Blower	3500-8760	500-1250	1750-11000
Heat Recovery Ventilator (2 fans)	2500-8760	70-300	175-2650
Induced Draft Blower	2000-3500	50-150	100-525
Bath Exhauster	200-4000	30-150	10-600
Range Exhauster	100-1000	100-300	10-300
Vacuum	50-200	500-1500	25-300
Clothes Dryer	100-400	75-150	10-60

Table 3.1 Annual Energy Implications of Various Movers in the Household

Static pressure losses depend primarily on flow velocity and distribution, turbulence, and component form. Sufficient dynamic head is required to project the air into the living space for mixing and local comfort considerations. Volumetric flow requirements are dependent on function and system components. Temperature rise for a constant heat input may govern flow rates for safety reasons (furnace output temperature no greater than 70°C). The capacities and efficiencies of heat pumps and air conditions are strongly affected by flow rates. Distribution of outside air may set a minimum flowrate requirement, as is stipulated in the CSA Standard F326. Buoyancy and duct design factors may limit how low a flow rate may be, to sustain an acceptable uniformity of distribution, particularly in the context of variable speed fans.

Some filtration devices depend on an adequate velocity to be effective (eg. face velocities of 2.5 m/s are needed for electrostatic-type filters), hence establishing minimum settings. Likewise, humidifiers may be governed by minimums established by the moisture capacity and evaporation rates of the carrying air. It is evident that the design of central air distribution systems and the requirements of the air handler are complex and interdependent. Any optimization of a blower performance must start with a clearly defined description of operating conditions. In the absence of a full, future consideration of all of the system parameters, there will need to be assumptions made here as to fan flow and static pressure requirements.

The same provisos also apply to residential ventilation systems that regulate air flows into and out of the building. Although their utility may seem more narrowly definable than recirculating central forced air systems, there is nothing straightforward about determining performance requirements. The fans must be capable of moving the volumes of air prescribed by building codes, but the static pressure losses are not specified. Regulation of pressure may also be a critical design parameter; to avoid combustion spillage, soil gas entry, or induced moisture problems. Conditions may need to be sustained over a wide range of impacts, interactive effects with the other air moving devices and fuel burning appliances, and variable flow rates. Control aspects of the system, as well as component interdependence, are critical determinants of fan performance.

Much of the installed exhaust equipment demonstrates airflow performance significantly below rated values (Ortech). For the purposes of this study, it is assumed that equipment is accurately represented by fan curves or rated capacities, at the rated pressure drop, in the absence of third party testing. We also assumed that they deliver at least the rated airflow in typical installations, have acceptable noise levels and are capable of operating continuously. For small, inexpensive equipment this is likely not the case.

Beyond aerodynamic efficiencies, performance effectiveness, and electrical usage, air handling systems should be evaluated in terms of their intended function. Creature comfort and healthy indoor air conditions may be sustained by a host of strategies that do not even require mechanical air moving. Current North American strategies may appear archaic in the near future, as environmental comprehension takes root. As building methods and products change, mechanical systems will adapt. If thermal loads become much smaller, the capacity and even the usefulness of forced-air circulation may render current considerations obsolete. Similarly, the requirements of mechanical ventilating for indoor air quality may be substantially altered by source reduction, regenerative technologies, improved ventilation effectiveness, and regulated natural ventilation.

It is arguable that efforts to improve the efficiency and effectiveness of air moving devices must not be isolated from considerations of their fundamental purpose and parameters. Advancements will be most productive when a comprehensive approach is taken and components are designed to suit the whole.

Nevertheless, current practices define a set of performance requirements for air handlers for which efficiency improvements may yield large savings. Future design and optimization will also have to build on a more complete knowledge of possible component performance. This study is, therefore, an important and fruitful starting point.

3.5 Practicalities and Industry Norms

The introduction of new practices and equipment in the residential HVAC industry has typically been gradual and incremental, by building on existing approaches. Homogeneity has more to do with the scale of equipment production than intrinsic technological virtues; witness the divergence between European and North American norms. Although radical strategies may deserve support, the likelihood is that modifications and improvements to existing products will bear most productively in the short term.

Central forced-air systems were typically designed for fan operation only when heating was required. When central cooling was added, operation was extended. Continuous recirculation has become common recently; with the growth in high-efficiency filter installation, fresh air distribution, and user preferences of steady low background noise over discontinuous fan operation. Equipment manufacturers are only now introducing products whose blowers can be speed-controlled efficiently.

Speed control technology has traditionally been limited to pulley wheels or multi-tap AC motors and these controls were used primarily to adjust for variations in field applications. Furnace manufacturers have also tended to select a blower capable of adjusting to a range of product capacities - to reduce tooling and stocking costs. Therefore, these capabilities for performance adjustment will likely remain important.

Current practice also assumes that furnace filters will be infrequently cleaned and sufficient excess capacity, to maintain required airflow with a plugged filter, is provided. Although alternative strategies are possible, such as a filter cleaning signal or automated cleaning services, it is likely that fans must continue to accommodate periodic increases in pressure losses (with a corresponding reduction in air flow rate).

Size constraints have become increasingly more significant to the manufacturer, endeavouring to keep cabinet metalwork and shipping volumes to a minimum, as well as to facilitate installation. Efficiency and noise levels have generally been compromised.

The emphasis on heating efficiencies has perversely affected air handling efficiency. Not only do extended heat exchanger surfaces, flow volumes, and face velocities increase aerodynamic load, but the resistive losses of the motor get inappropriate credit in North American test standards.

Most of the foregoing issues apply to ventilating equipment in general. Optimal performance of fans must be derived in the context of current practices. However, these externalities will hopefully change over the next decade.

4.0 EFFICIENCY OF AIR HANDLERS

4.1 Impacts of Energy Efficiency Improvements

For the purposes of this study, air handling efficiency can be expressed in terms of either power [W], or energy [J or kWh]. While ultimately the parameter of interest is energy consumption for environmental and cost considerations, technology comparisons are better done on instantaneous characteristics (power). The various power-based efficiencies can then be integrated over time of operation, for use in energy calculations.

Absolute air handler efficiency can be defined by how much power is required to provide a defined or imposed load:

$$\epsilon = \frac{Required\ Output\ Power\ [W]}{Input\ Power\ [W]}$$

The "Required Output Power" is the aerodynamic load imposed on or provided by the air handler. The total power delivered by the air handler [W] is the sum of the power contained in the total pressure of the moving air i.e. dynamic head, q, [Pa] plus the static pressure difference, ΔP [Pa], both developed at the required air flow, Q [m^3/s]. Dynamic or velocity head is $q = 1/2\rho V^2$.

$$Total\ Power = \frac{1}{2}\rho V^2 Q + \Delta P Q$$

Most residential air handlers are ducted systems in which the relative size of dynamic head is small, in the order of 5%, and it is convenient to define static efficiency as a measure of power conversion efficiency until the first, major improvements in components and systems have been made: The exceptions are ceiling fans, portable room fans and through-the-wall supply/exhaust fans, where a significant proportion of the power is contained in accelerating air from rest to the desired speed, and the static pressure term is small.

For most air handlers, then, the aerodynamic output power can be approximated by $\Delta P \times Q$ where ΔP is the static pressure, not the total pressure.

The input power is the electrical power provided to the air handler. If a motor had a power factor of 1.0, the Watts consumed would equal the power actually used to turn the rotor. However, there is usually additional current required to maintain the magnetic field, reducing the power factor below unity. The total power supplied the motor is called the volt-amps [VA], also in units of Watts, rather than power meter Watts. The current to maintain the magnetic field does not consume power at the motor, but incurs energy losses and capital costs for the utility.

Appendix B suggests a formula to account for total Watts consumed as a result of power factor performance. This formula has been used for efficiency calculations in this study.

It is instructive to briefly explore the magnitude and significance of the effect on the efficiency of a motor/fan set.

4.1.1 Effect of Flow Rate

Assuming static pressure drop and efficiency stay constant, the effect of reducing the flow rate is governed by the relationship identified above.

$$Load = \Delta P \times Q \qquad [W]$$

where: Q = Air Flow Rate [m^3/s] or [L/s]/1000
ΔP = Static Pressure Loss [Pa]

For turbulent flows, ΔP varies approximately with the square of the flow rate, Q, resulting in the load varying to the third power of Q:

$$Load = Q \times \Delta P = Q \times CQ^2 = CQ^3$$

(C is a constant based on system characteristics)

$$Load_2 = \left(\frac{Q_2}{Q_1}\right)^3 \times Load_1$$

This suggests that there is an **87.5%** reduction in required output power at a **50%** lower flowrate and demonstrates that, for an unchanging efficiency, significant reductions in input power are possible at even modest reductions in air flow rate.

4.1.2 Effect of Static Pressure

Assuming that both the air flow rate and efficiency stay constant, the variation of load with static pressure is linear. Thus, reduction of frictional losses produce proportional reductions in input power.

4.1.3 Effect of Efficiency

Input power is an inverse function of efficiency:

$$Input\ Power = \frac{Required\ Output\ Power}{\epsilon}$$

Typical efficiencies of bathroom exhausters are 3%. Their input power is over 33 times greater than the useful power demand. Another way of expressing this is that 32 times more energy is presently wasted than the work required to move the air. Raising the efficiency to 50% would reduce the input power to two times the useful power demand (decreasing waste by 1700%).

Clearly a great potential for reduction of fan power is afforded by significant improvements in air handler efficiency.

4.2 Efficiency of a Motor/Fan Set

The following efficiency summary really only applies to a motor/fan set based on "ideal" (i.e. developed or undisturbed flow conditions) for the type of fan in question. While the topic is clearly more complex than indicated by the efficiency summary, the list of efficiency components is nevertheless useful as a tool to categorize performance as discussed in the subsequent sections, particularly as it applies to fan/motor combinations. As stated in Section 2.0 Approach, the scope of the study is limited in that no detailed discussion is presented on the efficacy of connected duct systems and other "system effects". Similarly the efficiency which accounts for increased flow disturbance, ε_{f1}, is discussed but is not rigorously quantified (eg. Section 4.3 & Appendix D). Those discussions should be investigated in future work.

The efficiencies are grouped as motor-related (involving electrical power to motor shaft power conversion), fan-related (involving fundamental fan performance) and drive-related (involving both shaft and aerodynamic losses (including friction) between the motor and fan).

Clearly a great potential for reduction of fan power is afforded by significant improvements in air handler efficiency. It underlines the need to invoke systematic strategies beyond fundamental rated motor and fan performance.

Motor/Fan Set Efficiency

$$\epsilon_{mf} = \epsilon_m \times \epsilon_f \times \epsilon_d$$

ε_{mf} = efficiency of the motor/fan set
ε_m = efficiency of the motor
ε_f = efficiency of the fan
ε_d = efficiency of the drive

Motor Efficiency

$$\epsilon_m = \epsilon_{mr} \times \epsilon_{pf} \times \epsilon_l \times \epsilon_{sp}$$

ε_{mr} = rated efficiency at 100% load at fundamental speed
ε_{pf} = efficiency reduction based on power factor
ε_l = efficiency reduction due to part loading
ε_{sp} = efficiency reduction due to motor speed or load control

Fan Efficiency

$$\epsilon_f = \epsilon_{fr} \times \epsilon_{fl} \times \epsilon_b$$

ε_{fr} = tested or rated peak efficiency of fan, i.e. under developed flow in a given application

ε_{fl} = efficiency reduction accounting for actual application conditions or disturbance of developed flow

ε_{op} = off-peak reduction for operating at lower than peak static efficiency

ε_b = efficiency reduction due to bearing friction with respect to tested value without bearing loss

Drive Efficiency

$$\epsilon_d = \epsilon_{bd} \times \epsilon_{al}$$

ε_{bd} = efficiency reduction due to belt drive

ε_{al} = efficiency reduction due to aerodynamic loss imposed by motor placement in inlet airstream for direct-drive or belt-drive system

Note: If an efficiency reduction component does not exist, it should be dropped from the equation or ascribed 1.0, depending on the context.

4.3 Motor/Fan Set Efficiency vs. Air Handler Device Efficiency

To clearly define efficiencies, a distinction must be made between a motor/fan set and an air handling device. A motor/fan set can be the entire air handler, such as in the case of a ceiling fan or an in-duct booster fan, but often the air handler is a multi-component device (eg. furnace, heat recovery ventilator).

The performance of these multi-component devices is usually defined by desired flow and the external static pressure drop imposed by the connected ductwork and flow. Within the device, the fan/motor set can be exposed to significantly higher static pressures, at roughly the same flow. As a case in point, defining the actual operating parameters for a conventional furnace motor/fan set is difficult.

A furnace has been viewed primarily as a heating device with air flow requirements across the heat exchanger, rather than a true air handler. The design of furnace air handling usually violates many principles of good engineering practice (for example see (A.M.C.A.)). The sum total of poor air handling details will result in significant reduction in fan efficiency; however, little research has been conducted to quantify this effect. Some manufacturers try to execute the best design in a difficult situation, which is made worse by the trend to downsize equipment (partially for reasons of competing with non-forced-air heating equipment).

If a furnace were designed more systematically, i.e. fan upstream to allow developed flow, then the rated fan efficiency would be achieved. There would be a pressure drop associated with the furnace cabinet (to maintain the desired flow across the heat exchanger) but it would be more reasonable.

For example, if the furnace pressure drop with the fan mounted outside the cabinet is 85 Pa, the external static required is 100 Pa (including the A/C coil), the air flow is 600 L/s and the motor draws 750 W, then the motor/fan set and device efficiencies for the furnace, are as follows:

$$\epsilon_{mf} = \frac{185\ Pa \times 600 L/s}{1000 L/m^3 \times 750 W} = 15\%$$

$$\epsilon_{dev} = \frac{100 Pa \times 600 L/s}{1000 \times 750 W} = 8\%$$

This suggests that one can define an equivalent cabinet efficiency, ε_c, which equals 100 Pa divided by 185 Pa or 0.54; such that $\varepsilon_{dev} = \varepsilon_c \times \varepsilon_{mf}$.

As a result it can be noted that, if there is no design change within the furnace, the maximum device efficiency is 54%, with a motor/fan set operating at 100% efficiency.

The industry sizes furnace fans for equivalent cabinet static pressures ranges of 100 - 175 Pa, with the blower in the furnace cabinet, and 50 Pa - 125 Pa external to the furnace, depending on ductwork and air conditioning (Energy Technologies). While the assumed cabinet static pressure may not linearly translate into power requirements for reasons of flow interactions, for values of 150 Pa for the cabinet and 100 Pa for external static pressure losses, the efficiencies are as follows:

$$\epsilon_{mf} = \frac{250\ Pa \times 600\ L/s}{100 \times 750\ W} = 20\%$$

$$\epsilon_{dev} = \frac{100\ Pa \times 600\ L/s}{1000 \times 750\ W} = 8\%$$

The equivalent cabinet efficiency and maximum device efficiency (with 100% motor/fan set) would be 40%. We have only been able to discover one piece of field data with sufficient electrical and air flow measurement (B. Woods: personal communication). The furnace fan, prior to replacement with a high efficiency motor had the following characteristics:

$$\epsilon_{dev} = \frac{94\ Pa \times 500\ L/s}{1000 \times 550\ W} = 8\%$$

After a high efficiency AC motor replacement, the input energy was reduced to 410 W, thus increasing the device efficiency to 11%.

5.0 EFFICIENCY OF MOTORS, DRIVES, AND CONTROLS

5.1 Technology Description

(for a more detailed discussion see Appendix A)

5.1.1 Motors

The large majority of residential appliances use single-phase alternating-current (AC) induction motors. Induction refers to the voltage and current "induced" in the rotor (i.e. rotating part of the motor) by the rotating magnetic field occurring in the stator (i.e. non-rotating part). These motors have a characteristic speed (rpm based upon the number of pole pairs in the motor design). The actual motor speeds are usually lower due to "motor slip" and load imposed on the motor.

In North America, motors are commonly rated by power output with units of horsepower [Hp]. One Hp is equivalent to about 746 W. Note that a 250 W [1/3 Hp] motor with an efficiency of 30% actually draws 833 W of input power.

Motors for residential ventilation equipment and furnaces are in the fractional-horsepower range, that is 1/30 to 3/4 Hp. Improved fan and drive efficiencies would tend to downsize motor output requirements below 1/30 Hp.

Induction motors need an electromagnetic field to operate and current must be supplied to maintain the field. This current, being out of phase with the current that provides torque output, does no real work and is known as reactive power. Power consumed towards doing motor work is called active power. The ratio of active power to total power is known as the power factor. If the power factor is less than unity, additional energy must be supplied by the electrical grid to compensate for the losses incurred by the increase in current. While energy consumption is usually quantified from active power (i.e. at the house), total accounting should include the total power consumed to derive total energy consumption.

Conventional fractional Hp motors vary greatly in efficiency (discussed in the next section) and power factor. Shaded-pole motors are most common in the small sizes and have power factors ranging from 0.5 to 0.7. At the other end of the power factor scale are permanent split capacitor motors with power factors as high as 0.95. Appendix A gives a discussion of the effect of power factor on efficiency.

"High-efficiency" motors presently available are improved designs that minimize losses, but sometimes are no better than the motors produced prior to "least capital cost" efficiency reductions in the 1950's. Generally, efficiency improvements are due to improved overall design and the use of more appropriate materials for conductive windings, as well as a ferrous core. The best high efficiency motors are redesigned specifically to minimize losses. At 75% efficiency, high-efficiency 1/3 Hp furnace motors are about 50% more efficient than the conventional ones they replace.

A promising AC motor is the switched reluctance motor. In a reluctance motor the rotor does not require electrical excitation. Thus there are no rotor or electrical resistance losses by fundamental design, which is an advantage over induction motors. Traditionally, the reluctance motors were used for small, constant-speed loads such as timers and turntables. A speed-controllable variation, the switched reluctance motor, shows promise as a low-loss/high-power-factor AC motor in competition with ECM DC motors (see below). Apparently physical size can also be significantly reduced (S.R. Drives Ltd.).

There is also work being done on simple methods of synthesizing three-phase power from single-phase residential service, thereby allowing the use of inherently more efficient three-phase motors used in commercial and industrial installations.

One type of DC motor is the electronically-commutated motor [ECM]: a brushless, permanent magnet type motor. The brush-commutator combination is replaced by an integrated circuit which switches polarity to the windings of the stator. The polarity reversal is similar to AC motors, with the difference being that the reversal rate can be directly controlled at the motor. ECM and AC motors are compared in the chart below.

ECM Motor over AC Motor

Advantages:	Disadvantages:
Minimal rotor losses and high power factor due to permanent magnet	Increased cost over single-phase AC motors
Inherently speed controllable Speed control programmable for specific applications	Can generate harmonics and electronic noise, creating problems for the utility and consumer electronics

Table 5.1 Advantages and Disadvantages of ECM Motors Over AC Motors.

5.1.2 Motor Drives and Speed Controls

All except the smallest fans have traditionally been driven by belts, in order to link motor shaft output to fan input. This allowed some optimizing of fan rpm for a particular application, by use of pulley diameter ratios. In residences, only the larger furnace blower typically used a belt drive, because compactness was not an issue and flexibility for field conditions was considered a positive feature. Range hoods, exhaust fans and HRV's have small, direct-drive fans. Increasingly, furnace fans are being outfitted with direct drive, by inserting the motor in the intake opening of the airstream, for purposes of motor cooling (which is important for low-efficiency motors, and of almost no consequence for very high-efficiency motors) and compactness.

The large potential for energy savings resulting from tailoring motor output to variable imposed loads has driven development of electronic AC motor speed control technology; the most fundamental of these is the multi-speed or multi-tap motor. However, this strategy is never really efficient because only some of the pole windings are used for most speeds, so the "active" conductor is only a fraction of the total installed conductor. Magnetic material utilization is also reduced. Further, the lowest speed is usually not less than 70% of full-rated speed, which is not adequate for many applications (eg. low speed for HRV).

The simplest electronic adjustable speed drive [ASD] is the sliding transformer tap or resistance tap variety (similar to incandescent light dimmer switches) that can vary voltage, thus changing rpm and torque. If compatible, it can be combined with a multi-speed motor to minimize input power in a constant-flow application. Some, however, show little reduction or actually increase input power to the speed controller, when motor output needs are reduced.

Many automatic electronic ASD's have been developed for larger motors. Speed control is usually used to reduce motor output (i.e. variable torque) to match changing loads. The most common technology used for fractional Hp induction motors is the voltage-source inverter ASD. Since motor speed is proportional to the frequency of the AC waveform, the AC supply is converted to DC power and reinverted to a frequency-adjustable and voltage-adjustable AC waveform.

A residential retrofit product, the Green Plug (see Appendix A), can sense the operational characteristics of motor loading, i.e. current and motor slip, to minimize input energy for a given motor load (eg. refrigerator compressor).

These relatively expensive electronic ASD technologies compete with the highly efficient and controllable ECM motor. ECM's are available with electronic erasable programmable read-only memory [EEPROM] chips that allow a customized application algorithm to be used for motor control. This "managed" output produces dramatic reductions in input power when output needs are reduced, producing almost constant efficiencies throughout.

For fan technology, there is a benefit in simply changing the motor's speed characteristics, essentially for the same load, enabling different, more efficient fan designs to be used (see Section 7.2). Alternatively, direct-drive furnace blowers require lower speed motors than belt-drive furnace blowers. Low-speed motors, however, are inherently less efficient. A higher-efficiency, speed-controlled motor may have a higher resultant efficiency in this application.

5.2 Motor Efficiency

Improving motor efficiency for small air handlers is a very recent phenomenon. Most present ventilation equipment uses conventional low efficiency motors. The efficiencies and applications of the predominant types are given below:

Motor Type	Application	Output Watt [Hp] Range	Efficiency
Shaded Pole	Bathroom exhausters, range hoods direct-drive furnaces, air conditioning & fan coils, HRVs.	1-200 [1/1000 - 1/4]	10% - 25%
Capacitor Start	Continuous ventilation, furnace (belt-drive).	40-2000 [1/20 - 3]	35% - 50%
Permanent Split Capacitor	Central ventilation, HRVs, furnace.	10-2000 [1/100 - 1]	35% - 50%

Table 5.1 Overview of Motor Types, Efficiencies and Applications.

The efficiencies shown above are rated efficiencies (i.e. at 100% load). The following sections describe characteristics which may reduce AC motor efficiency under normal use:

Motor Loading

At 40% loading, conventional motor efficiency is usually in the order of 50% or less of the rated efficiency.

Motor Speed

The higher the fundamental speed (i.e. the fewer the number of poles) the higher the efficiency. For example, an 1800 rpm (4 pole) motor is about 7% more efficient than a 1200 rpm (6 pole) motor. (Note that direct-drive furnace blowers must use a lower rpm motor than belt drives, since the fan has not been redesigned for higher rotation speeds).

Power Factor

The lower the power factor the higher the total power consumed, but power factor is also affected by motor loading and speed. An example of conventional motor characteristics and resulting efficiencies is given in the Table 5.2. Note that the efficiency reduction due to motor loading , ε_1 is 1 at 100% load and 0.5 at 40% load. (PF = power factor).

		PF	$\varepsilon_{mr} \times \varepsilon_1$	ε_{pf}	ε_m'
3600 rpm	100% load	0.85	60%	98%	59%
	40% load	0.50	30%	85%	26%
1200 rpm	100% load	0.78	54%	96%	51%
	40% load	0.45	27%	81%	22%

Table 5.2 The Effect of Power Factor and Loading on Motor Efficiency

The following table gives the relative input power corresponding to the efficiencies above. (100% load = 1 unit of output power)

		Output Power	**Input Power**	**Input Power (P.F. modified)**
3600 rpm	100% load	1.0	1.67	1.70
	40% load	0.4	1.33	1.54
1200 rpm	100% load	1.0	1.85	1.96
	40% load	0.4	1.48	1.81

Table 5.3 The Effect of Motor Load and Power Factor on Motor Input Power

Note that at the house, these motors would draw almost as much power at 40% load as at 100% load. If total utility power is considered, there are cases where input power can actually be greater.

There are several incidences where significant research effort has been expended on the fan aerodynamics and even the motor housing aerodynamics, but the fundamental motor technology is still conventional. Some manufacturers of high-end furnaces and heat pumps have started incorporating ECM motors, partially for direct increases in fan efficiency, but more to provide multi-stage air flow and capacity of their equipment. This allows air circulation, which tends to be increasingly continuous (for heating, cooling, filtration and ventilation), to occur at a much lower time-averaged input power. ECM motors exhibit rated efficiencies of 68% to 80%, compared to 35 - 50% for permanent-split-capacitor motors. Their actual, in-place efficiencies are much higher than conventional motors.

Electric utilities offer incentives for use of more efficient motors for furnace blowers to reduce electric demand. They specify a minimum efficiency at rated Hp. To be considered as high efficiency, 1/3 Hp induction motors must operate at 71% to 74% efficiency; at an 100% load rating this is an efficiency improvement in the order of 45%.

Future motor designs, with integrated-circuit, programmable speed controls, should be able to operate at close to 90% efficiency at 100% load and 85% efficiency at 40% load.

5.3 Drive Control Efficiency

Conventional belt drives using V-belts typically experience losses, due to belt slippage, in the order of 13 - 15% [ε_{bd} = 85% - 87%]. If belts are properly maintained and loosened to the point of minimum slippage, the loss is around 10% [ε_{bd} = 90%]. The use of a more sophisticated synchronous belt can all but eliminate this loss and maintain the flexibility of adjustable fan speeds. The efficiency effects of aerodynamic losses of pulley belt assemblies, as tested at Ontario Hydro, was ε_{al} = 83%. Direct drive arrangements have no drive losses, but increase aerodynamic losses to the fan, because the motor is in the air stream. Actual efficiency reduction is specific to the aerodynamics of motor housing, size and location. (It is possible to actually improve blower or fan efficiencies because of motor shape effects, although that is unlikely in household equipment.) Conventional direct furnace blowers can have an aerodynamic effect efficiencies, ε_{al}, of 80%.

AC adjustable speed drive [ASD] efficiencies can vary depending on design, but tend to be high [ε_d = 95%] at rated speed. However, they have a higher tendency to drop with load than ECM motors. At 40% load, the variable-torque type may have a drive efficiency of 85%, down from 95%.

6.0 FAN EFFICIENCY

6.1 Technology Description

There are three main types of fans: centrifugal, mixed flow, and axial. Figure 6.1 (Daly) gives a static-pressure-to-flow comparison for different fans that have a 'total-pressure' x 'flow' output of 10 kW.

Narrow centrifugal fans have high static-pressure to flow ratios while other centrifugal fans satisfy a broad, mid-range of static-pressure to flow ratios. Free air axial fans produce high flows at minimal static pressure, but vane axial fans (which use inlet or outlet vanes to develop additional flow characteristics) compete with mid-range centrifugal fans.

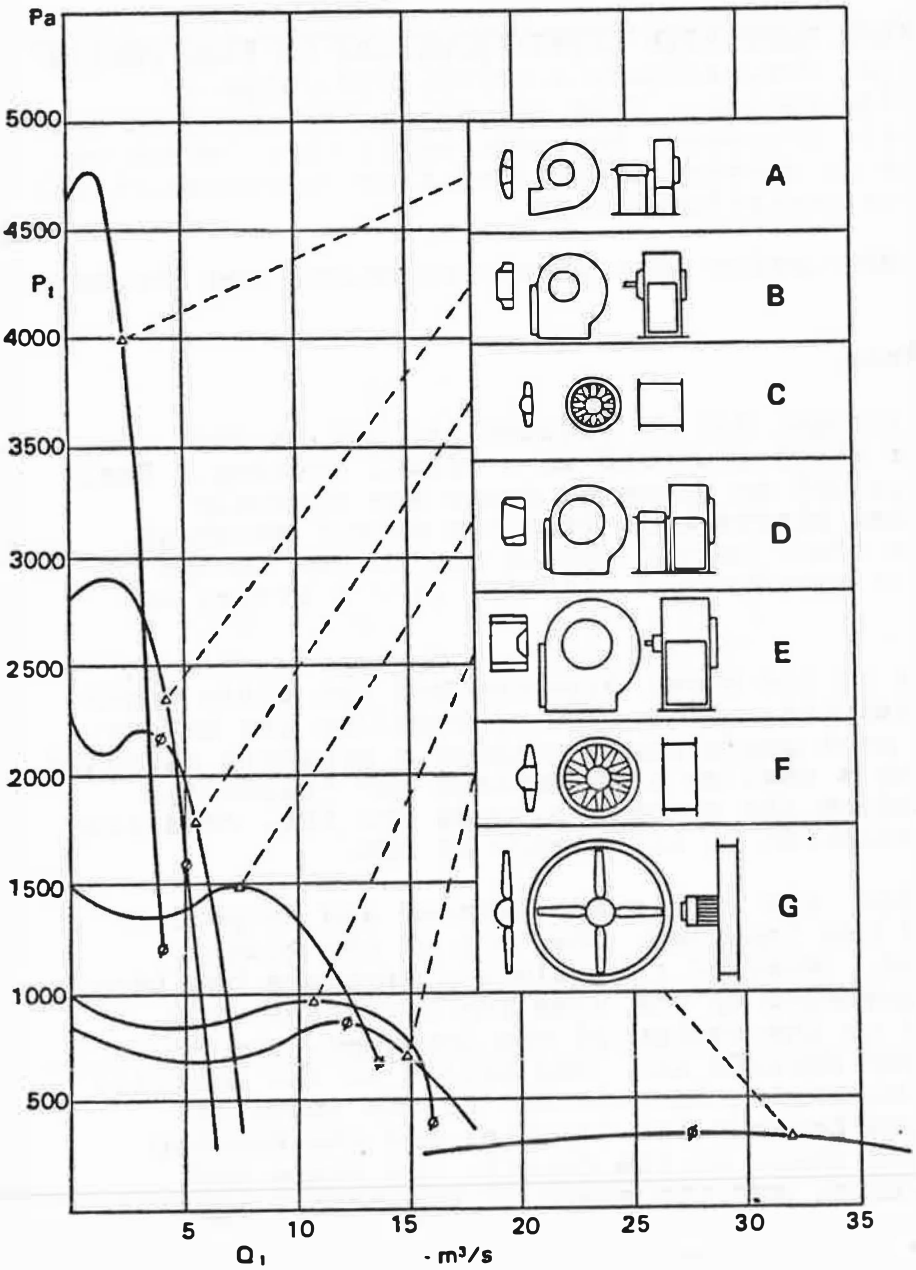
For a more detailed discussion than presented below, see (Torin).

6.1.1 Centrifugal Fans

The most common centrifugal fan in residential use is the forward-curved blower wheel enclosed in a scroll housing. Small impellers in the 50 to 250 mm diameter range are commonly fabricated with punched blades bent from the parent material. Often, the blades are flat; better wheels use formed strips of metal approximating an aerodynamic airfoil. These strips are connected with tabs to the outer ring and backplate, which allows for optimization of spacing of the blades. Typically the impeller width is 50% of the wheel diameter and the blade depth is about 8% of the diameter. This type of impeller can become unstable and exhibit poor performance without a properly designed scroll housing. Often a smaller than optimum (or "tight") housing is used to reduce the overall size of the fan, resulting in a corresponding reduction in efficiency of 20%.

In a forward-curved fan, the air is accelerated and propelled from the periphery of the impeller, then out of the scroll opening, at high speed. Most of the velocity pressure has been converted to static pressure by the time the air leaves the housing. In addition to the design of the impeller, the performance of a blower depends on: the design of the housing; the diameter of the inlet ring in relation to the impeller diameter; the clearance between the impeller and the housing inlet; the location and shape of the cutoff; the shape and dimensions of the housing; and the shape of the scroll opening.

A physical inspection of relatively small ventilation and furnace fans shows significant gaps between the impeller and housing inlet (some big enough to put your finger in) suggesting large reductions from potential peak efficiencies. It is also interesting that a standard by the Japanese Standards Association (J.S.A.) for belt-driven centrifugal fans specifies minimum tolerances for certain design parameters, one of which is inlet gap. This standard stipulates the clearance as being no more than 1/150th of the impeller diameter, but need not be less than 3 mm.



A Backward-curved Half-width 630mm 42 rev/s 13·5 kW at Δ 17 kW at Ø

B Backward-curved Full-width 630mm 36 rev/s 12 kW at Δ 14 kW at Ø

C Axial 50% hub 630mm 48 rev/s 13·5 kW at Δ 15 kW at Ø

D Forward-curved centrifugal 700mm 18 rev/s 15 kW at Δ 30 kW at Ø

E Multi-vane centrifugal 850mm 9 rev/s 15 kW at Δ 30 kW at Ø

F Axial 35% hub 1000mm 24 rev/s 13 kW at Δ 15 kW at Ø

G Axial 25% hub 2000mm 12 rev/s 12·5 kW at Δ 14 kW at Ø

Each fan, operating at top speed and best efficiency point Δ is chosen for an output $Q \times P_t = 10$ kW.

Peak input power is taken at Ø

Drawings are to a uniform scale of 1:100

Fig. 6.1 Comparative Fan Designs at Equal Output Power (Daly, pg. 133 - 134).

Increasingly, backward-inclined impeller designs are available. As the name indicates, the tip of the blade faces backwards with respect to the wheel rotation. This causes the air to leave the wheel with a lower effective velocity and a higher static component than a forward-curved design, and therefore loses less energy from converting velocity pressure to static pressure in the scroll or casing. For this reason, it is also not necessary to rely on a scroll housing (e.g. FanTech), and backward-inclined impellers are sometimes used with cylindrical housings at an efficiency loss, but with simplicity and cost advantages.

In this case, outlet vanes are sometimes used to improve the static performance, by reducing the outlet swirl component. Outlet vanes tend to have blades that are spaced further apart which may be useful in small impellers, where otherwise tight blade spacing may limit performance, due to blade roughness or boundary layer effects. The inlet cone/impeller interface is designed differently for these fans, than in forward curved fans, to minimize inlet clearance (see Fig 6.2 (Wright)). Small clearances are more important, due to the higher static pressure at the impeller. (An overview of design issues affecting centrifugal blowers is given in Appendix B).

A special centrifugal fan application is the induced-draft combustion exhaust blower which operates at relatively high static pressure and low flow (eg. 625 Pa @ 25 L/s). Narrow, backward-curved and paddle-wheel blowers are two technologies that have the desired characteristics.

6.1.2 Axial Fans

Axial fans propel air in an axial direction and without stators, in a swirling tangential motion created by the rotating propeller-type blades. The impeller consists of contoured blades rooted in a hub, with a specified pitch angle (angle between blade and plane of rotation) that varies from hub to tip. There are three types of axial fans:

1. Free-air
2. Propeller
3. Ducted

Free air or circulating fans have no aperture at the blade tips and usually draw air from, and supply air to, the same space. These fans operate at a higher velocity pressure than static pressure. Examples are room ceiling fans and conventional portable fans.

Most axial air handlers are fans with an orifice or tube surrounding the tips of the fan blade. A propeller fan is essentially a free-air fan mounted inside an opening in a plate; however, the shape of the orifice can vary considerably, and improve airflow characteristics.

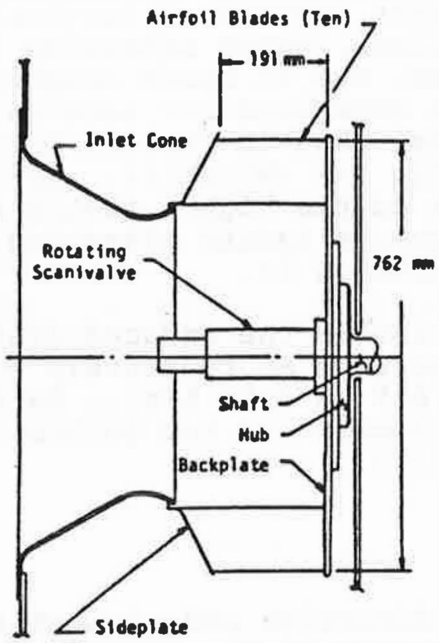


Fig 6.2 Inlet Cone Impeller Detail at Clearance (above) (Wright, pg. 908).

If the cylindrical orifice is extended before and after the blade, the fan is termed a "tube-axial". The optimum position for the blades is a distance downstream of the inlet orifice equivalent to about 30% of the axial length of the tube. Tube-axial fans usually have smaller tube depth to diameter ratios than vane-axial fans.

Vane-axial fans are ducted fans that have outlet straightening vanes (stators), for static pressure recovery from the tangential (swirl) component of air flow. Another method is to use inlet vanes designed to "pre-swirl" the air so that the outlet flow is mostly axial in nature. They also develop high static pressures. Two counter-rotating fans, moving air in the same axial direction but with compensating swirls, would result in essentially axial flow and more static power rise for a given package size and flow rate.

Maintaining low tip clearances can substantially improve flow performance and efficiency. However, clearances below 1.5% of the blade diameter do not substantially improve flow performance (Torin) in residential and industrial designs.

The efficiency of ducted axial fans is significantly affected by adding ductwork beyond the inlet and outlet of the tube, as are the fan performance characteristics (eg. flow stability). A better technology for some ducted applications is the in-line backward-curved centrifugal.

For specialized non-ducted applications, such as through-the-wall exhaust or supplying to a plenum, tube-axial fans and vane-axial fans may be the fan of choice.

6.1.3 Mixed Flow Fans

A more complicated blower wheel combines both axial and centrifugal flow, and is known as a "mixed-flow" (see Figure 6.4 (Torin). This type of fan may have a role as an in-line fan, similar to the backward-curved centrifugal, if the wheels can be produced cost effectively (eg. by plastic casting). However, the efficiency seems to be lower by about 10%.

6.2 Selection of Appropriate Fans for Applications

Maximum efficiency is typically not the prime determinant of residential fan selection. Availability, physical size, motor speed, flow configuration (90° versus in-line), plus noise, vibration, and cost are some of the factors that deter the manufacturer from using the more efficient fan technology. In many cases, however, the wrong technology is being used, simply because the fundamental conditions of the application have not been examined.

Three non-dimensional parameters can define fan characteristics (Torin):

1. Specific Speed

$$N_s = \frac{N\sqrt{Q}}{0.011\ \Delta P^{0.75}}$$

2. Pressure Coefficient

$$\psi = \frac{6.1\times10^{8}\ \Delta P}{N^2 D^2}$$

3. Flow Coefficient

$$\phi = \frac{6.1\times10^{6}\ Q}{WND^2}$$

for centrifugal or mixed flow

$$\phi = \frac{2.4\times10^{7}\ Q}{D(D^2-d^2)\,N}$$

for axial flow

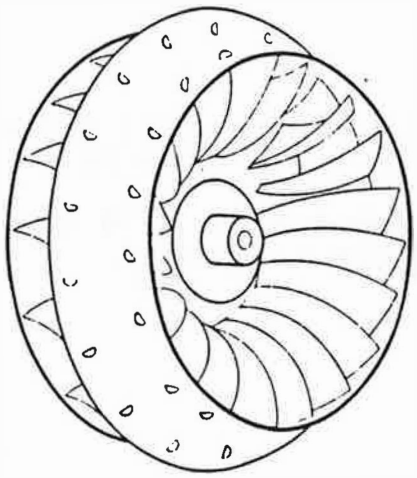
where:

N	=	impeller speed [rpm]
Q	=	air flow [L/s]
ΔP	=	static pressure [Pa]
D	=	impeller diameter [mm]
W	=	impeller width [mm]
d	=	hub diameter of axial fans [mm]

The latter two coefficients establish impeller dimensions for static pressure and flow versus rotational speed. Specific speed combines the three fan performance factors, N, Q, and ΔP_2 in one design parameter. One can calculate the specific speed for any given fan or fan type, and compare it to the static efficiency of the various fan technologies (Fig. 6.5).

These generalized curves were developed from tests on many geometries of fans of each type and represent a reasonable picture of the characteristic efficiencies. However, within each fan technology there are better and worse designs. For example, large backward-curved centrifugal fans, with aerodynamic blades, can have static efficiencies as high as 90%, versus the 72% for a backward-curved centrifugal shown on Table 6.5.

The following table gives some typical residential fan applications in terms of specific speed, fan types, and efficiencies. The fan rpm, N, is often limited by available motor rpm, if a direct drive configuration is used. The table shows both the typical rpm and optimum rpm (for maximum efficiency), on the assumption that speed control is available.



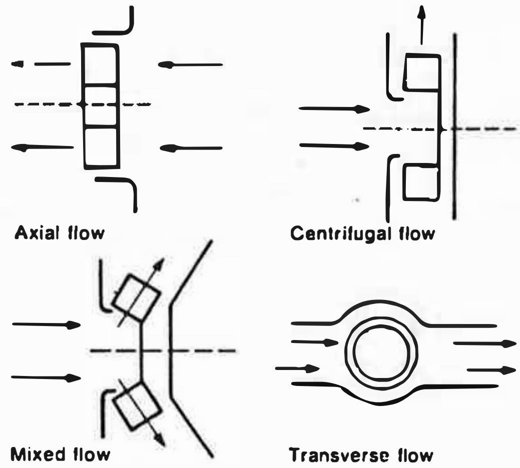


Fig. 6.3 Comparison of Mixed Flow With Other Flow Configuration; Mixed Flow Impeller (Torin pg. 12, 17).

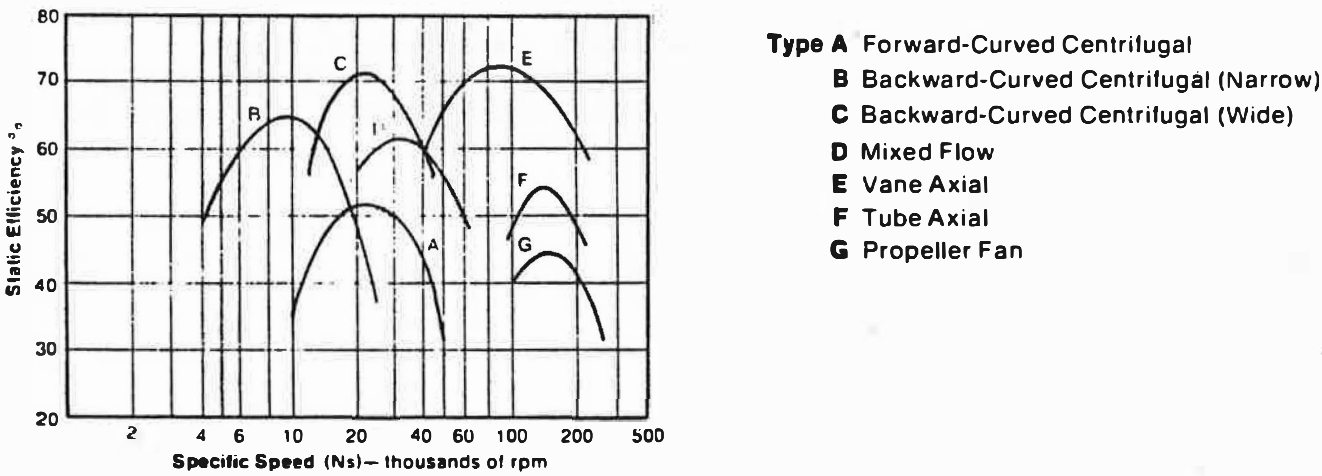


Fig. 6.4 Static Efficiency Performance vs. Specific Speed for Different Fan Types (Torin, pg. 30).

At any specific speed the impeller dimensions can be derived from the flow and pressure coefficients. Using a forward-curved centrifugal furnace fan (47% efficiency) the following parameters and dimensions result:

N_s = 3700
ψ = 1.65
ϕ = 0.35
D = 290 mm
W = 115 mm

The industry is more likely to use a double-inlet fan of a smaller diameter to depth ratio with D = W = 225 mm.

For a backward-curved centrifugal furnace fan (72% efficiency), the following corresponding values are calculated.

N_s = 22,000
ψ = 0.7
ϕ = 0.05
D = 750 mm
W = 200 mm

Clearly, the more efficient solution is a fan of a much larger diameter.

The above discussion is for illustration purposes only. It is interesting to note, (Ariewitz) reports that a blower was developed for a flow of 665 L/s at ΔP = 271 Pa and 1092 rpm (specific speed 38,000) with a diameter of 413 mm and width of 146 mm, performing at a fan efficiency of 66%. This blower wheel is about 2/3 the size calculated above.

6.3 Fan Efficiencies

Although larger, engineered centrifugal fans have maximum efficiencies up to 70% for forward-curved and 90% for backward-curved types, more typical peak static efficiencies are given in Figure 6.5 and are as follows:

Forward-Curved Centrifugal	52%
Backward-Curved Centrifugal (narrow)	64%
Backward-Curved Centrifugal (wide)	72%
Mixed-Flow	62%
Propeller	44%
Tube-Axial	54%
Vane-Axial	73%

APPLICATION		Q [L/s]	ΔP [Pa]	N [rpm]	N_s [rpm]	FAN TYPE	ε_f %
Furnace Blower		550	225	1000	37000	F/C	47
						M/F	62
				600	22000	F/C	52
						B/C	72
Bathroom Exhaust		25	25	1700	69000	F/C	low
						V/A	71%
				1000	41000	M/F	60%
						F/C	42%
HRV	High Flow Rate	180	150	1700	36000	F/C	46%
	Low Flow Rate	40	25	700	36000	M/F	61%
						B/C	62%
	High	100	150	1000	22000	F/C	52%
	Low	40	25	400	22000	B/C	72%
Combustion Exhauster		25	625	1700	6000	B/C/N	60%

F/C = forward-curved centrifugal
B/C = backward-curved centrifugal (wide)
B/C/N = backward-curved centrifugal (narrow)
M/F = mixed flow
V/A = vane axial

Table 6.5 Specific Speed Consideration for Various Fan Applications

Forward-curved centrifugal fans, for heating/cooling applications with motors in the air stream, often have fan efficiencies around 35% instead of 60% (Ariewtz) for reasons mentioned in Section 6.1 and Appendix B. From the combined efficiencies of smaller fans given in Section 7.2, and assuming shaded-pole motors at 20%, the fan efficiency is around 10% or less.

On the other hand, our search on fans (Appendix D) turned up examples of both forward-curved and backward-curved centrifugal fans with efficiencies of 65% and vane axial fans with efficiencies of 70%. Thus improvements of almost one decimal order of magnitude are possible, if fans are properly designed and then operated at their peak efficiency point.

7.0 COMBINED AIR HANDLER EFFICIENCIES

7.1 Range of Efficiencies

Based on Section 4.0 (Efficiency of Motors, Drives, and Controls), Section 5.0 (Fan Efficiency), Appendices A, B, and D, and allowing for some reasonable interpretations, Table 7.1 summarizes the range of values for the efficiency components identified in Section 4.0 Efficiency Definition.

COMPONENT	EFFICIENCY RANGE	COMMENT
Rated Motor Efficiency, ε_{mr}	0.10-0.90	Depends on motor type
Power Factor Reduction, ε_{pf}	0.50-0.99	Power factor 0.25-0.9
Part Load Reduction, ε_{l}	0.30-1.00	Minimum load 20%
Speed Control, ε_{sp}	0.85-0.95	ECM speed control included in ε_{mr}
Rated Fan Efficiency, ε_{fr}	0.40-0.80	
Flow Reduction, ε_{fl}	undefined	See Appendix D
Off-Peak Reduction, ε_{op}	0.50-0.95	depends on fan curve location
Bearing Reduction, ε_{b}	0.89-0.99	Sleeve or ball-bearings
Belt Drive Reduction, ε_{bd}	0.80-0.99	Non-aerodynamic
Drive Inlet Reduction, ε_{al}	0.80-1.00	Motor/drive at inlet

Table 7.1 Range of Values of Various Efficiency Components

Which values apply to a specific air handling application is rooted in a long decision process involving manufacturing, marketing, economics, and technical issues. To bring some meaning to the efficiency range discussion, four levels of efficiencies relating to air handlers are defined that have meaning in terms of technical improvement of the technology, as well as the manufacturing/market context, to achieve that goal.

The four defined levels of efficiencies that relate to air handlers are:

1. Poor
2. Typical
3. Best current
4. Potential

The first three levels should be self-explanatory after examination of the example in Table 7.2. The technical "potential" relates to the likely best performance for a marketable product in the year 2000.

The example of efficiency improvements presented in Table 7.2, relates to a furnace blower application. Note that optimum fan efficiency, ε_{fp}, rather than the manufacturer's rated fan efficiency, ε_{fr}, is used.

The combined efficiency is presented both as a motor/fan set efficiency and an overall air handler or device efficiency as defined in Section 4.2 (Efficiency of Motor/Fan Set). It is assumed that parallel improvements in the furnace cabinet "efficiency" occur, commensurate with overall fan efficiency. Note that cabinet efficiency, ε_c, is also the maximum device efficiency for an 100% efficient motor/fan set.

Table 7.2 suggests that there could be a ten to one spread in between poor and best current motor/fan set efficiencies, and a fifteen to one spread in device efficiencies. If a standard stipulated the 'typical' efficiency as a minimum performance criterion, moving to the technical potential could still increase the efficiency by a factor of three.

Actual combined motor/fan set efficiencies for air handlers smaller than furnace blowers were solicited both domestically and internationally (see Appendix D). The information is primarily derived from manufacturers' information, some of which is based on tested equipment. Effort was made to source state-of-the-art equipment, including technology being developed by a NASA contractor for the planned orbiting space station.

Conventional exhaust equipment ranged from less than 1% (for equipment which is assembled from pieces on-site) to 2% for better quality products.

Eastern Air Devices has a variety of different technologies (forward curved and radial centrifugal fans, vane axial fans, tube axial fans and mixed-flow) and, except for very small sizes, efficiencies ranged from 9% to 21%. A major manufacturer of backward-curved in-line fans, Kanalflakt, quoted performance in the 9 to 19% efficiency range. It may be noted that this company seems particularly conscientious in their aerodynamics, including placement and aerodynamics of the motor housing (supplied by EBM), but the AC motor electricals are otherwise of conventional efficiency. Efficient motors in these fans could produce quite efficient motor/fan sets, in one relatively-easy step.

	POOR	TYPICAL	BEST	POTENTIAL
ε_{mr} **Motor**	0.40 Capacitor	0.50 PSC	0.80 ECM	0.90 ADV
ε_{or} **Off-rating**	0.65	0.80	0.98	0.99
ε_{fp}	0.65	0.65	0.85	0.90
Fan Type	F/C	F/C	B/C	B/C
ε_{dr} **Design Reduction**	0.65	0.85	0.85	0.90
ε_{op} **Off-Peak**	0.70	0.80	0.90	0.95
ε_{d} **Drive**	0.85 Belt	0.90 Belt, DD	0.99	0.99
ε_{mf} **Motor/Fan Set**	0.065	0.16	0.51	0.69
ε_{c} **Cabinet**	0.20	0.40	0.55	0.70
ε_{dev} **Device**	0.013	0.065	0.28	0.48

ε_{mr} = rated motor efficiency
ε_{or} = $\varepsilon_{l} \times \varepsilon_{pf} \times \varepsilon_{sp}$ - takes into account motor load, power factor, speed control
ε_{fp} = peak static efficiency of optimum design
ε_{dr} = reduced fan efficiency due to poorer features (clearance, blade design, tight housing, bearings)
ε_{op} = off-peak reduction for operating at lower than peak static efficiency
ε_{d} = drive losses from belt drive or aerodynamic loss by motor or belt drive being in air stream for direct drive

F/C = forward-curved centrifugal
B/C = backward-curved centrifugal
Belt = belt drive
DD = direct drive

Table 7.2 Efficiency Improvements for a Furnace Fan

A blower, assembled by the authors from engineered off-the-shelf forward-curved blower parts, and tested several years ago in the Air Changer fan test rig, exhibited an apparent 36% motor/fan set efficiency. The motor was a high-efficiency, three-speed, permanent-split capacitor motor.

Motor/fan combinations of note in Appendix D are ECM centrifugal blowers used by Water Furnace (26%), an axial fan from Advanced Design and Manufacture (22%), and vane-axial and mixed-flow (30%) fans from Woods.

Ceiling fans cannot be rated on static efficiency as mentioned in Section 4.0. Calculations, based on information given in Figure 7.1, result in a 47% efficiency, on the assumption that the air is accelerated to the velocity profile shown. In actual fact, the efficiency may be somewhat lower if one considers that, after start up, not all of the air is accelerated from rest.

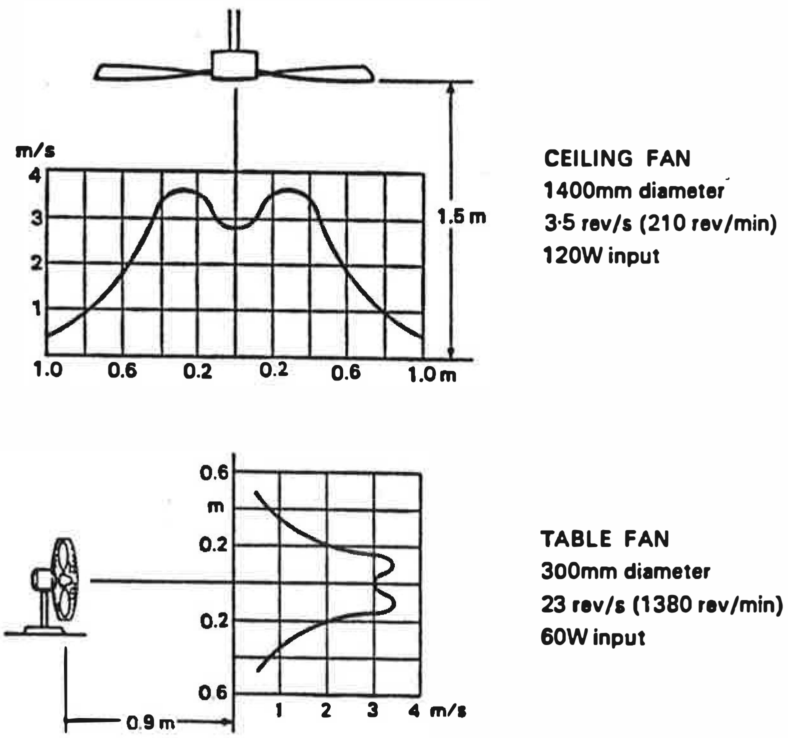


Fig. 7.1 Velocity Profiles of Typical Ceiling and Table Fans (Daly, pg. 37).

7.2 Input Power and Energy Reductions

Improvements in overall efficiency of air handlers reduce input power proportionally with $1/\varepsilon$, given an unchanging air handling load (required output). For example, if ε_{mf} improves from 20% to 50%, for an air moving load of 125 W, the input power savings are 375 W or 60%. For continuous operation this translates into 3300 kWh annually. At $0.08/kWh, that is an annual saving of $264, if the unit were operated continuously, or of $106 if it were run 40% of the year.

With any speed control technology which is able to maintain high efficiencies at even low motor loads, significant additional savings are realizable, without further changing the fundamental motor and fan technology. Two example AC motor applications, with and without electronic adjustable speed drive (ASD) controls, are examined in Table 7.3.

System A: HRV **Continuous low speed ventilation fan with intermittent high speed (assume ε_f = 55%)***

	Flow [L/s]	Static [Pa]	Loading [%]	Speed [rpm]	ε_m [%]	Input [W]
Low Speed	50	31	12.5	575	20	14
High Speed	100	125	100	1150	60	38
Low Speed w/ASD	50	31	100	575	55	5.1

Run times - High 5%, Low 95%
Time-averaged input power saving 56% [8.5 W]
Annual Savings 74 kWh ($6 at $0.08/kWh)

System B: Furnace **Continuous Three-Speed/Variable Speed Furnace Fan (assume ε_f = 55%)***

	Flow [L/s]	Static [Pa]	Loading [%]	Speed [rpm]	ε_m [%]	Input [W]
Single Speed	500	250	100	1150	60	378
Multi-speed w/ASD						
Low Speed	100	2	-	230	51	0.7
Med. Speed	300	90	20	690	54	91
High Speed	500	250	100	1150	57	400

Run times - Low 50%, Medium 20%, High 20%
Time-averaged input power savings 76% [288 W]
Annual Savings 2500 kWh ($200 at $0.08/kWh)

Table 7.3 **Effect of Speed Control on Energy Consumption.**

Note: The fan efficiency would drop somewhat at a lower rpm, but that is a much smaller effect than the motor efficiency changes being illustrated here.

8.0 ECONOMICS OF EFFICIENCY IMPROVEMENTS

8.1 Cost Issues

Industry Context

Current industry norms have primarily been driven by least capital cost with minor consideration of performance, longevity, and operating costs. Often, the user does not perceive a performance deficiency as in the case of a bathroom fan that is assumed to be exhausting provided you can hear it. Builders have tended to install equipment of short life expectancy, suited for occasional use but meant to be operated continuously. The energy consumption of air handling in general has been a blind spot for virtually everyone from consumers to utilities, and even energy experts.

In the absence of market mechanism or any compensating measures, the North American industry is dominated by low-efficiency, low-cost, short-lived residential air movers.

Industry Incremental Cost Considerations

Typically, trades pay about 2 times, and retail purchasers 3 times, the manufacturing cost of mechanical equipment. An incremental cost of upgrade may be considered to translate as a three-fold cost to the consumer for cost-benefit analysis. This may, however, be overly conservative. Where the development of an improved product can be accompanied by production efficiency improvements, as has frequently been the experience of new appliance lines, there may be offsetting savings. In a competitive market, an increase in commodity price while maintaining or increasing sales volumes may require smaller mark-up and still be profitable.

The type of intervention to rectify impediments to optimal efficiencies can have a major impact on cost. For example, a utility subsidy, applied to the retail price, may have three times the impact when provided to the manufacturer, if conventional mark-ups apply. On the other hand, mandatory efficiency standards may result in virtually no cost increase in the long term, due to compensating retooling savings; however, continued advancements tend to be curtailed. It is therefore highly speculative to predict future costs and economic potential.

Incremental vs. Total Installed Costs

The relative cost increase in efficiency improvements is most appropriately expressed with respect to installed costs. For example, better bearings might represent a doubling of the cost bearings, but represent 1% of the total cost of a blower installation. Indeed, the virtue of an upgrade should be based on performance improvement and operating cost savings.

Cost Reduction Opportunities

It should not be assumed that energy efficiency improvements necessarily cost more. Many of the improvements discussed are simply design changes that only require retooling investment. Taken in combination, there may actually be potential for reducing costs for certain items such as lower capacity motors.

8.2 Cost of Early Improvements

One measure of the incremental costs to be expected for short-term upgrades is to compare typical with best available technology.

For bathroom exhaust fans, dealer prices of less than $20 are reported. A median quality unit with cabinet may retail for $60 and presumably manufactured for about $20. Device efficiency would typically be about 3%.

Best available technology consisting of formed-plastic, backward-curved blades, improved housing, and a brushless DC motor, yields a device efficiency of 20% for peak external static/flow conditions. This equipment is currently available for $250 dealer/installer price. The similar technology with a PSC AC motor, at an efficiency of 10%, costs $100.

For a second case, a forced air heating appliance is examined. The OEM cost for a typical furnace blower, with PSC standard efficiency motor and forward-curved direct-drive impeller, is approximately $75. Based on static pressure external to the device, an efficiency of 7% is assumed.

For an ECM DC motor, backward-curved impeller, the OEM cost is likely less than $200. Actual costs were not provided by manufacturers, but this may be interpolated from overall equipment pricing. Setting aside the system efficiencies of variable speed operation, the device efficiency is estimated at 30%.

8.3 Payback and Present Worth of Early Improvements

The conventional, less sophisticated, evaluation of cost effectiveness of an energy upgrade is payback:

$$\textit{Payback (Years)} = \frac{\textit{Incremental Costs}}{\textit{Annual Energy Savings}}$$

Table 8.1 shows the paybacks of the components described above. Note that Paybacks are less than 1 years, except for the DC exhaust fan, which has a payback still significantly less than 5 years.

Present worth considerations provide a more useful estimation of cost-effectiveness in terms of how much money would need to be set aside today, subject to an assumed interest rate, that would pay for the capital cost. For the purpose of this study, the lifetime of the equipment was taken as 15 years (this ignores the fact that low efficiency equipment may actually be replaced sooner).

The relevant methodology is as follows

e = escalation rate of electricity = 10% per annum
i = discount rate or cost of money = 6% per annum

$$a = \textit{Effective Interest Rate} = \frac{i-e}{i+e} = 0.036$$

PW = present worth of energy costs = C x P
C = annual electrical cost to run fan
P = present worth multiplier

$$P = \frac{1-(1+a)^{-n}}{a} = 20.4 \quad \textit{for } n=15 \textit{ years}$$

Therefore the present worth of energy cost use in Table 8.1 equals PW = C x 20.4.

Total present worth is the sum capital cost and present worth energy cost.

Assuming continuous operation, the present worth savings for the exhaust fan are 4 and 19 times the incremental cost and for the furnace, over 60 times. The present worth energy cost would drop proportionately for operation of less than 100% of the year.

8.4 Costs of Long Term Improvements

Although there are some costs available on certain component upgrades, their use in predicting longer-term improvements is questionable. For example, ECM motors in the 1/6 Hp range cost $90 OEM, versus $30 for a standard PSC motor. Switched reluctance motors, which can outperform the brushless DC type, may actually be **less** expensive than PSC motors, in high-volume production. Likewise, aerodynamic plastic impellers with close tolerance housings, and high quality bearings, are potentially competitive with current metal fabrication, but require significant capital investment. Other upgrade features such as entry/exit conditions and optimized sizing, load matching etc. do not necessarily have a cost penalty.

Of course, improvements above and beyond those cited in this report are conceivable and may entail increased costs. However, if device efficiencies of about 50% are indeed realized without cost penalty, there may be little motivation to proceed further, having achieved an order of magnitude reduction in operating costs.

Exhaust Fan	**ε [%]**	**Capital Costs**	**Power [W]**	**Annual Energy Costs**	**Payback [Years]**	**Total Present Worth**	**PW Savings**
BASE	3%	$60	85.0	$60	-	$1,260	$ -
AC Upgrade	10%	$100	25.0	$18	1.4	$470	$790
DC Upgrade	20%	$250	12.5	$ 9	3.7	$430	$830
Furnace Fan	**ε [%]**	**Capital Costs**	**Power [W]**	**Annual Energy Costs**	**Payback [Years]**	**Total Present Worth**	**PW Savings**
BASE	7%	$75	700.0	$490	-	$2,350	$ -
Upgrade	30%	$200	165.0	$115	0.3	$10,000	$7650

Table 8.1 Payback and Present Worth of Device for Base and Upgrade Fan Technology (run continuously @ $0.08/kWh)

9.0 DEVELOPMENT OF AN ENERGY EFFICIENCY STRATEGY

9.1 Air Handling Energy Implications

Blowers, in total, consume perhaps a third of our electricity (Larrson). A significant portion of these blowers are fractional horsepower accounting for an estimated 20% of the blower load. The potential for load reduction and efficiency improvement is greatest among the smaller air handlers. Residential air handlers account for an estimated two third's of the fractional horsepower blowers, or 5% of the total national electrical consumption. The R-2000 program has modified its assumed lighting and appliance load upwards from 5,000 kWh/yr to 8,000 kWh to reflect monitored results. This additional 3,000 kWh can likely be attributed to the furnace blower and continuously-operating ventilators.

In a previous study by the authors for CMHC (Allen Associates F326) the annual operating energy for continuous ventilation was estimated to be 7000 kWh, for houses employing the furnace fan for distribution, based on a power input of 80 W for each of the two fans in a heat recovery ventilator, and 400 W for the furnace blower. At a typical $0.08/kWh, the two HRV fans cost about $110 per annum to operate, and the furnace blower consumed a further $280, for a total of almost $400 per annum. With increasing rigour in ventilation requirements in Canadian building codes, plus growing demand for continuous air conditioning including mechanical cooling, humidifying, and filtration, we may expect major increases in electrical demand - unless stringent measures are taken to radically improve present efficiencies.

9.2 Barriers to Improved Air Handler Efficiencies

In the absence of intervention, it is unlikely that market forces would result in significant improvement in air moving performance or efficiencies. The existing vast gap between cost-effective potential and current industry norms is sufficient testimony. For change to happen, barriers must be understood and - either eliminated or overridden.

Interviews with representatives of the residential HVAC industry reveals the basis for lack of action (Sheltair) and (Bowser).

Barriers include:

Cost

The incremental production and purchasing costs for high efficiency air handlers is modest with respect to total installed cost of the equipment (a $15 bathroom exhaust fan costs over $100 installed).

The economic return on efficiency improvements would justify moving beyond the best commercially available air handlers. Cost barriers are principally related to development, redesign, retooling, testing and start up.

Comprehensive Redesign

Optimal solutions to reducing input power entail changes to the motor/fan set, in conjunction with cabinet, control component and configuration modifications. These larger applications have higher risks and costs attached. Fundamental departures require both internal management coordination and significant research, development, and other financial and time commitments.

Canadian Manufacturing

Most manufacturing firms and component suppliers are either branch plants or out-of-country. Canadian-made standards are therefore difficult to effect without U.S. cooperation. (The U.S. Department of Energy has, however, expressed great interest in this research and its implications.)

Higher Risk Factor of Innovation

Mass production of high-cost consumer goods requires that failures and side-effects are scrupulously avoided. Rapid introduction of significant change is impeded by this aversion to problems.

This applies to furnaces, heat pumps, and, to a lesser extent, heat recovery ventilators.

Convention

Innovation in the housing industry is characteristically stifled and air handlers are no exception. Long-established products and practices tend to be viewed as "self-evidently optimal" despite any evidence to the contrary. Persistence is seen as being of mutual benefit to the manufacturer and the builder.

Knowledge

Although some component manufacturers are informed about the performance of their products, the performance of the assembled devices and the impact of application and installation on efficiency, are not well understood. Likewise, purchasers and users are virtually unaware of either the energy demands or the operating costs of these products.

9.3 Strategic Measures

Without initiatives taken by industry, government, and/or utilities, it is highly likely that the status quo will be maintained. The full economic opportunity to substantially reduce residential energy demand will only be captured if a comprehensive strategy is developed. Some of the components that would significantly contribute to such a strategy are listed below.

Research

Research, including: user surveys, current product performance, field measurement, design parameter testing and analysis, and other foundation work must be carried out.

Testing and Standards

Performance testing and rating standards, plus modifications to existing standards and procedures, to reflect aerodynamic efficiency and electrical load characteristics, need addressing.

Minimum efficiency standards, such as applied to certain products in Ontario and under development federally, may be applied to air handling devices.

Design Development

Development of improved design practices, plus tools with a technology transfer component to the industry, are required.

Incentives

Incentives, such as competitive mass purchase, prototype testing, provision of expertise, and market promotion will assist in motivating manufacturers to undertake product changes.

Programs

Special programs, targeted at retrofit, should be explored and developed.

Programs such as R-2000, plus those for social housing and other institutional bodies with a stake in both energy and housing, could develop specifications and requirements that would secure markets for high-efficiency equipment.

Awareness programs, including presentations to key organizations and conferences, information brochures for targeted audiences, publications, and industry seminars would accelerate adoption and initiative.

Labelling

Performance and energy labelling of products will assist in purchasing discrimination, conformance inspection, and market competitiveness.

Lead Agency

An appropriate lead agency, possibly CMHC, could provide the overall coordination for developing and implementing a strategic plan. A coordinating committee of participants and affected parties would then be struck, with the lead agency acting as secretariate.

9.4 Achievable Energy Efficiency Targets

In order to establish some measure of the timeline for bringing on higher efficiency equipment, some consideration of the availability, cost-effectiveness, and sequencing of technological improvements must be given.

There are several easy upgrades available for existing equipment, requiring little adjustment by manufacturers and device assemlers. Examples are: use of high efficiency AC motors; proper matching of motor to shaft power requirements; improved bearings; tighter tolerances between impeller and housing; and low slippage belts. These are achievable in the short-term and should require only modest information support to achieve adoption. Some of these improvements could result in paybacks of less than one year.

More substantial improvements, to a near-term (seven year) target, would reflected the best currently-available equipment. Characteristic features include: "smart" adjustable speed drive, retooling of impeller and housing for better aerodynamics, modifications to cabinets and configuration; and optimization of the type and sizing of fans. This level of performance is approximately a four-fold improvement in efficiency for furnaces - and an order of magnitude improvement for air exchange devices. Annual energy cost savings are likely to yield paybacks well under five years, based on current cost differentials between typical and best-available technologies.

Advances in air handling equipment, beyond best practice, is likely to yield a further doubling of efficiency, and additional energy savings when coupled to flow rate control strategies. Motor advances are already well underway in other applications. New fan designs, suited to end-use and integrated with the device as a whole, can yield large improvements. Advances in fabrication will further enhance aerodynamics and tighten tolerances.

Development should be encouraged now, so that, in seven years these levels of efficiency can become the industry norm. It should be borne in mind, however, that future applications and systems will likely alter the design parameters - so that a comprehensive (or system) approach is highly advisable.

10.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the information collected, air handling equipment efficiency may be less than 1% for small air exchange devices, and as low as 10% for a furnace fan/motor set; 3% when considering the furnace as an air handling device. On the other hand, the spread of efficiencies of available fan/motor sets is in the order of ten to one. Input powers are, therefore, often more than an order if magnitude higher than delivered air flow power. This situation is not supportable from either an operating cost or environmental point of view, but is ripe for improvement.

There is a major lack of design and research information on fan technology smaller than furnace fans, limiting the certainty of efficiency potential predictions. As well, information on the aerodynamics within air handling devices (eg. furnaces, HRV's) is virtually nonexistent.

A major field study of existing furnace and ventilation power requirements, plus system operating parameters should be undertaken. This study should, with similar urgency, survey annual operating times of air handlers. Other information that should be assembled is an inventory of smaller air handlers (actually all appliances) in the household, plus data on duct leakage. There would be a major cost savings to the sponsor over what is possible if a segregated study approach were undertaken.

The consultants therefore recommend:

1. Establishment of a committee of concerned parties, to develop an industrial strategy and program support;

2. Development of requisite standards and testing facilities, in support of efficiency rating of air handlers;

3. Modification of existing standards, as required to reflect the electrical load and performance furnace blowers and ventilating devices; and,

4. Provision of research and development support from government and utilities, to improve the availability of efficient technology.

ANNOTATED BIBLIOGRAPHY.

A.M.C.A. (Air Movement and Control Association) Inc. Fans and Systems. Arlington Heights, Ill., U.S.A.: A.M.C.A. Inc., Publication No. 201-90, 1990.

Alberkrack, Jade. "Selecting Brushless DC Motor Controllers", *Machine Design*, August 11, 1988: 109-114.

Allen Associates. Displacement Ventilation For Energy-Efficient Houses. Energy Mines and Resources, March, 1990.

This is a review of current state of displacement ventilation detailing an idea for a dehumidification strategy. Heating, cooling, and fan energy are shown to be significantly reduced using this strategy.

Allen Associates. Potential Impacts of Proposed CSA Standard F326: Residential Mechanical Ventilation Requirements. Canada Mortgage and Housing Corporation, January, 1990.

American Council for an Energy Efficient Economy, Washington, D.C. and Berkley, California with Universitywide Energy Research Group, University of California. Energy Efficient Motor Systems: A Handbook on Technology, Program, and Policy Opportunities (Contract No. DE-AC65 86WA00467). Golden, Co., U.S.A.: Western Area Power Administration, 1991.

Ariewitz, D. et al. "A High Efficiency Indoor Air Mover", *ASHRAE Transactions*, Vol. 89, Part 2B, DC-83-13, No. 3, 1983.

This paper describes the prototyping of a 46% efficient blower/motor assembly moving 1405 cfm at 1.09 inches of water. Changes to the assembly which resulted in this doubling of efficiency included moving the motor from the typical flow restricting location in the eye of the blower wheel, changing from a forward curved to a backward curved vane, and a high efficiency fractional horse power motor.

Baumeister, D. Fans. 1st Edition. New York: McGraw-Hill Book Company, 1970.

Bowser Technical. Report to Allen Associates on Improving Air Movement Efficiency: A Program for Change. Bowser Technical, 1993.

Carlisle, Ben. "Brushless Motors Carve Out a Niche", *Machine Design*, March, 1988: 109-113.

Chardon, Carlo C. "Fan Selection and System Evaluation Techniques", Conference Record - Midcon, 1982, Distr. by Western Periodical Co., North Hollywood, Calif., U.S.A. El Segundo, Calif., U.S.A.: Electronic Conventions Inc., 1982.

Clifford, George E. Heating Ventilating and Air Conditioning. Reston, Virginia: Reston Publishing Company, 1984.

Daly, B.B. Woods Practical Guide to Fan Engineering. Colchester, England: Woods of Colchester, Ltd., 1978.

This is a textbook on all aspects of fan engineering including fans and fan performance, fan drives and controls, fan duty cycle, and noise.

Dumont, Rob. "Energy Answers (Energy Efficient Motors)", Sol, No. 87, March - April 1992: 18.

Edwards, P. Effect of Blower Bearings and Drive Type System Performance of Belt Drive Systems. Ortech Report #35-11662, 1991.

Embleton, T. F. W. "Experimental Study of Noise Reduction in Centrifugal Blowers", The Journal of Acoustical Society of America, Vol 35, #5, May 1963.

Fleisher, William A. "How to Select DC Motors", *Machine Design*, November 12, 1988: 99-103.

Geddes, W.D., and Allen Associates. Investigation and Survey of the Furnace Blower Assembly Market. Ontario Hydro, 1991.

Furnace manufacturers, heating wholesalers, and blower manufacturers were surveyed to gather information on the types and numbers of residential blowers sold, and their willingness and ability to go to high efficiency assemblies.

Grenwald, E.K. "The Hidden Costs of Oversizing Motors", Plant Engineer, Vol. 42, No. 11, 1988: 84-85.

This is a short article on the effects of oversizing motors, with most attention paid to the power factor effect. Power factors decrease with loads below full-load, resulting in extra demand charges and decreased plant and utility capacity.

Hamdi, E.S. and M. Bradford. "Analysis, Performance, and Application of Composite-Rotor Motors", Proceedings of the Seventh International Motor-Con '85 Conference. Hannover, Germany: Intertec Communications, 1985.

Hamilton, J.J. Passive Dehumidification and Air Circulation, Ventilation System for Northern Rural Housing in Alberta. Alberta Municipal Affairs, June, 1991.

This paper addresses the issue of moisture removal in northern rural Alberta, where mechanical ventilation systems or envelope upgrades are unlikely due to cost and supply availability. Working with these conditions, the author suggests a stack-effect driven, glass-fibre-board vent system to remove moisture with little energy penalty and no discomfort to residents. The system has been lab tested but not field tested.

International Electrotechnical Commission Standard. A.C. Electric Ventilating Fans and Regulators for Household and Similar Purposes. Geneva: International Electrotechnical Commission Standard, 1980.

A standard on performance and methods of testing residential ventilation fans. The standard does not include energy efficiency requirements.

Japanese Standards Association. Japanese Industrial Standard: Forward-Curved Bladed Fans JIS B 8331. Japanese Standards Association, 1983.

Johnson, K.A. and G. Pitts. "Experiments with a Passive Ventilation System: Paper 9", Energy Efficient Domestic Ventilation Systems for Achieving Acceptable Indoor Air Quality, 3rd A.I.C. Conference. London, UK: 1982.

Jorgensen, R. Fan Engineering, Seventh Edition. Buffalo, New York: Buffalo Forge Company, 1970.

Lovins, Amory B et al. State of the Art: Drivepower. Snowmass, Co.: Competitek^{sm} (E Source), April, 1989.

Marbek Resource Consultants. Minimum Efficiencies Levels for Fractional HP Motors: Phase 1 Report. Canadian Electrical Association, Research and Development, March, 1990.

Marbek Resource Consultants. Minimum Efficiencies Levels for AC Polyphase 1-200 HP Motors. Canadian Electrical Association, Research and Development, September, 1989.

Neise, W. "Review of Noise Reduction Methods for Centrifugal Fans", Journal of Engineering for Industry, May 1982, Vol. 104: 151-161.

Ontario Hydro. Effect of Blower Bearings & Drive Type on System Performance of Belt Drive Systems, Ontario Hydro Research Division Report No. TSDD-92-004, 1992.

Ontario Hydro. High Efficiency Motors in Residential Furnaces. Ontario Hydro Retrofit Program Information, 1992.

Ontario Hydro. Performance Optimization of Fan, Pump and Blower Systems Field Handbook. Ontario Hydro, 1992.

Ontario Hydro. "Power Factor" and "High Efficiency Motors", Ontario Hydro Energy Management Series. Ontario Hydro, 1990.

These two booklets explain principals of high efficiency motors and power factor. The "Power Factor" booklet explains how Ontario Hydro accounts for power factor effects in the billing of large customers.

Ontario Hydro. Procedure for the Field Testing of Fans. Ontario Hydro Research Division Report No. TSDD-91-058, 1991.

Oregon State University, Energy Extension Programme. Super Good Cents Book. Portland, Oregon: Bonneville Power, 1991.

Ortech International. Furnace Fans and Blower Systems: An Investigation Into System Interactions - Effect of Blower Bearings and Drive Type on System Performance of Belt Drive Systems. Ontario Hydro Research Division Report No. 35-11662/ ET-91-054, 1991.

Ontario Research Foundation (Ortech International) and HRAI Technical Services Division. Residential Exhaust Equipment. Canada Mortgage and Housing Corporation, 1988.

Parkins, Lynn M. "Experimental Passive Stack Systems for Controlled Natural Ventilation", CIBSE National Conference, n.d.: 508-518.

The testing of several installed Passive Stack Ventilation systems; includes flow velocities under a wide range of meteorological conditions and the affects of bends in the duct and duct diameter are discussed.

Petersen, Stephen R. and George E. Kelly. "Economic Analysis of Efficiency Improvements to Residential Gas- and Oil-Fired Central Heating Equipment". Symposium Papers - Future Alternatives in Residential and Commercial Space Conditioning. Chicago, Ill., U.S.A.: Institute of Gas Technology, 1981.

Phelan, J.J., Russell, S.H., and W.C. Zeluff. "A Study of the Influence of Reynolds Number on the Performance of Centrifugal Fans", *Journal of Engineering for Power*, Vol 101, October 1979.

Prairie Agricultural Machinery Institute. Summary of Ventilation Fan Reports. Prairie Agricultural Machinery Institute, March, 1986.

This report provides detailed information on agricultural axial fans. Information includes total efficiency and cfm per watt for several fans. Efficiencies vary significantly from one fan to the next and from low speeds to high speeds.

Proskiw, G. Utilization of Residential Mechanical Ventilation Systems. Efficiency and Alternative Energy Technology Branch (CANMET), Energy Mines and Resources, Canada, 1992.

Raj, D., Swim W.B. "Measurements of the Mean Flow Velocity and Velocity Fluctuations at the Exit of an FC Centrifugal Fan Rotor", *Journal of Engineering for Power*, Vol. 103, April 1981.

S.R. Drives Ltd. Switched Reluctance Drives. Leeds, UK: S.R. Drives Ltd., October, 1988.

Sheltair Scientific Ltd. The Residential Duct and Chimney Survey. Canada Mortgage and Housing Corporation, 1989.

Sheltair Scientific Ltd. Barriers to the Use of Energy Efficient Residential Ventilation Devices: A Survey of Industry Opinion, and A Review of Strategies for Change. Canada Mortgage and Housing Corporation, March, 1993.

Shephard, D.G.. Principles of Turbomachinery. New York: MacMillan Publishing Co. Inc., 1956.

Smith, W. A., O'Malley, J. K., and A.H. Phelps. "Reducing Blade Passage Noise in Centrifugal Blowers", *ASHRAE Transactions*, Vol. 80, Part 2, 1974.

Torin Corporation, Designing with Moving Air. Torrington, Connecticut: Torin Corp, n.d.

This is a short handbook on fan and motor selections including efficiencies of different fan and motor types and the maximum efficiency points for fan types.

Varley, F.A. "Effects of Impeller Design and Surface Roughness on the Performance of Centrifugal Pumps", *Proceedings of the Institute of Mechanical Engineers*, Vol. 175, #21, 1961.

White, Jim H. Telephone interview. July 28, 1992.

Woods, B. G. Letter to the authors. July 17, 1992.

Woods, B. G. High Efficiency Furnace Blower - Product Development Strategy. Ontario Hydro Research Division, Report No. 92-247-K, December, 1992.

Woods, B. G. Impact of Installing High Efficiency Motors in Domestic Furnace Blowers. Ontario Hydro Research Division, Report No. 91-283-H, December, 1991.

Wright, T. "Centrifugal Fan Performance With Inlet Clearance", *Transactions of the A.S.M.E.*, Vol. 106, October, 1984: 906-912.

APPENDICES

APPENDIX A: MOTOR AND DRIVE TECHNOLOGY

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Motor Power Rating

Motor powers are always stated as output power, while virtually every other device is rated as an input power. This anomaly is not always caught in energy publications, and can significantly underestimate motor power, and energy use, since motor efficiencies of 10% mean that input powers are 10 times output powers.

AC Motors

Two basic types of AC motors are synchronous motors and induction or asynchronous motors.

Synchronous motors have a revolving magnetic field at the stator that matches the speed of the rotor. Both the rotor and the stator are connected to the external circuit and the motor operates only at the synchronous speed (for definition, see below), no matter what the load (up to a certain limit). It must be brought up to synchronous speed by auxiliary means, usually another motor or a starting winding and, if the imposed load is too large to maintain synchronous speed, the motor simply stops.

These motors are used for special applications where a constant speed is essential, e.g. clocks or timing mechanisms. (They also have the ability to generate as well as absorb reactive power and can be used to improve power factor in large plants, see Power Factor, below.)

Induction or asynchronous motors usually only deliver power to the stator, to produce a rotating magnetic field which induces a voltage and current in the rotor, due to the speed differential. The induced current causes the rotor to follow the rotating field and run slightly slower than the field speed. This reduction in rotor speed, with respect to the synchronous speed, is known as "slip". The amount of slip is usually 1% to 10% and is smaller for larger motors. Figure A.1 shows the output versus rpm performance of standard and high efficiency 1/3 Hp motors.

Synchronous Speed

The synchronous speed of the rotating magnetic field in an induction motor depends on the frequency of the supply voltage and the number of pole pairs in the motor. For a voltage frequency of 60 Hz:

$$\textit{Synchronous Speed (rpm)} = \frac{3600}{\textit{no. of pole pairs}}$$

A four-pole motor (two pole pairs) has a synchronous speed of 1800 rpm.

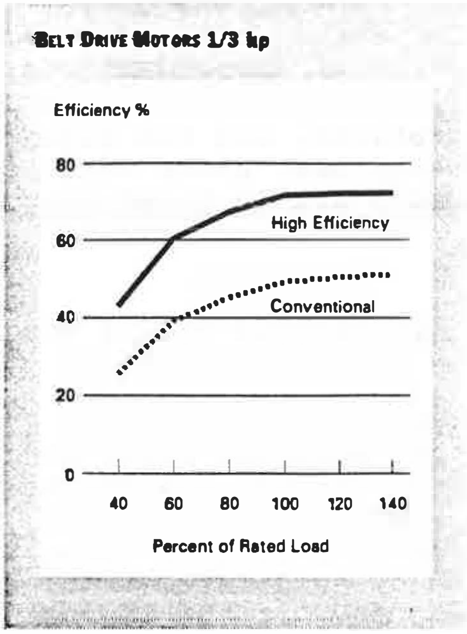


Fig. A.1 Efficiency of a Conventional (PSC) and High Efficiency Motors vs. Motor Loading (Ontario Hydro).

Single Phase vs. Three Phase Motors

Induction motors can be run on single- or three-phase power. The large majority of motors are single-phase but, being small in size, account for about 20% of the motor power (WAPA). Houses are supplied with single-phase power which, for ventilation fans and furnace blowers, disallows (at the present time) the use of inherently-more-efficient, three-phase induction motors. Researchers are working on ways of synthesizing three-phrase electricity from single-phase (Dumont).

Induction Motor Losses

Losses are usually classified as "no-load" losses and "load-dependent" losses. No-load losses include friction losses (in bearing seals and sometimes brushes), and windage (air resistance of the rotor), and core losses (hysteresis and eddy current losses in rotor and stator magnetic materials).

Load dependent losses occur mainly as resistive and stray load types. Resistive losses, also called I^2R or power losses, are proportional to the square of the current and the resistance of the windings. Resistivity increases with temperature so that improvements resulting in cooler running temperatures tend to also reduce I^2R losses.

Induction Motor Losses (Cont.)

Stray load losses is a grab-bag term for at least eight loss mechanisms, all of which increase roughly by the square of the current or load. Understanding of them is quite limited but can often be sensitive to motor design and manufacture.

Types of Induction Motors

The common induction motors are shaded-pole, split-phase, capacitor-start, and permanent-split-capacitor. Table A.1 is a comparison of the relative characteristics of these motors. The permanent split capacitor is the best of these, with a maximum efficiency of 60% and a power factor as high as 95%.

Induction motors with efficiencies of up to 90% are increasingly being developed and made available. The term "high efficiency" motor does not seem to have a rigorous definition, but refers essentially to motors that have efficiencies higher than those shown in Table A.1. Essentially they are motors that are being fundamentally re-engineered to minimize the losses of more conventional motors.

Some unique, flexible motor designs can maintain efficiency (85%-90%), while operated in single-phase, three-phase or DC modes, e.g. Magnetics Research International motors. They are also capable of variable speeds and modifiable for leading, lagging and unity power factor. This design has been used in a front-loading washer design.

High-Efficiency Improvements

Generally, stated motor efficiency in AC induction motors can be improved by:

1. Using more and better "active" materials (conductive windings and ferrous core).

2. Improving design (geometry of "active" materials). Redesign typically yields the higher efficiency gains.

Decreasing electricity prices and aluminium/copper cost ratios in the 1950's and 1960's encouraged the use of thinner, less efficient conductors and cores such that efficiencies of motors of 1950's vintage were more efficient than those produced in the 1960's and early 1970's. Some motors advertised as "high-efficiency" have simply the same performance of motors from the 1950's.

Type of Motor	Shaded Pole	Split Phase	Capacitor Start	Permanent Split-Capacitor
Description	Single Phase—starting torque provided by a permanently short-circuited auxiliary winding.	Single Phase with auxiliary starting winding connected in parallel with main winding. A starting relay is needed.	A modification of the split phase. The auxiliary starting winding is connected in series with an external capacitor.	A modification of the split phase. The main and auxiliary windings, in series with a continuous duty capacitor, are in the circuit at all times.
H.P. Range	1/1000 to 1/4	1/20 to 1	1/20 to 3	1/100 to 1
Rated Speed (60 Hz)	1050, 1550, 3100	860, 1140, 1725, 3450	860, 1140, 1725, 3450	1075, 1625, 3250
% Efficiency	10 to 40	35 to 60	35 to 60	30 to 60
Power Factor	.50 to .70	.55 to .70	.55 to .70	.85 to .95
Starting Torque (% of full load)	20 to 80	90 to 200	160 to 350	30 to 100
Application	Direct drive, low-power fans requiring long life without maintenance.	Suitable for frequent starting of fans and blowers—in direct and belt drive units.	All purpose motor for high starting torque, low starting current—in direct and belt drive units.	For direct drive units and multi-speed operation.
Advantages	a. Inexpensive b. Multi-speed operation c. Compact	a. Good starting torque b. Medium efficiency	a. Very high starting torque	a. Very high efficiency and power factor b. Steep speed-torque curve c. Multi-speed operation d. High inherent impedance protection e. Reversing operation f. Quietest of all small induction motors
Disadvantages	a. Low efficiency b. Low starting torque	a. Not applicable for special characteristics such as high starting torques, high efficiency and power factor, constant or adjustable speed	a. More expensive b. Non-adjustable speed	a. Low starting torque b. Speed varies under load

Table A.1 Motor and Drive Technology - Commonly Used Induction (Fan/Blower) Motor Types (Torin).

True high-efficiency motors are essentially redesigned motors which minimize many of the inherent motor losses. Some ways to minimize inherent motor losses are:

1. Utilization of copper conductors, instead of aluminium, reducing resistance by 60%;

2. Utilization of larger diameter conductors and more core material;

3. Utilization of "soft" magnets, to increase flux density and to allow flux to readily change in size and direction (thus reducing losses due to hysteresis and eddy currents) (see Table A.2);

4. Utilization of high performance bearings (important to maintain the smaller air gaps used on higher efficiency motors); and,

5. Optimization of motor dimensions or improved tooling.

typical good-quality carbon steel	10.-11.
low-grade silicon steel	7.9
medium-grade silicon steel	5.5
modern nonoriented silicon steel	2.-4.
grain-oriented silicon steel	1.2
best laser-scribed production steel	1.1
best doubly-oriented lab silicon steel	0.4
amorphous pre-production FeNiBSi	0.3
best lab FeNiBSi	0.03-0.1

Table A.2 Progress in Reducing the W/kg Losses of Soft Magnetic Materials at ~1.5T/60 Hz (Lovins).

Efficiency of AC Single-Phase Motors

The scope of this study is residential air handlers which are all provided with single-phase power.

Analysis, performed at CMHC, on fractional horsepower motors suggests that efficiencies for conventional efficiency motors between 1/6 Hp and 3/4 Hp follow a relationship of:

$$\epsilon_m = -11 + 7.35 \ln (\textit{rated shaft power, W}) \qquad [\%]$$

which results in efficiencies of 35.5% and 24.5% for 3/4 Hp [560 W] and 1/6 Hp [125 W] motors respectively. By extrapolating this relationship, a 1/100 Hp [7.5 W] motor could have an efficiency as low as 4%. Figure A.3 tends to substantiate this relationship.

An efficient European motor, designed specifically for small air moving equipment, does not follow this trend, exhibiting efficiencies between 40% and 50%, at powers down to 1/30 Hp [25 W]. Larger, conventional motors from Germany produced under tighter standards, result in motor efficiencies only slightly lower than North American high efficiency motors (see Fig. A.4).

Testing done at Ontario Hydro, on 1/4 Hp and 1/3 Hp furnace blowers, resulted in efficiencies of about 50% for standard motors and about 75% for high efficiency motors (see Table A.3). The above efficiencies are assumed to be at 100% loading or at rated shaft power.

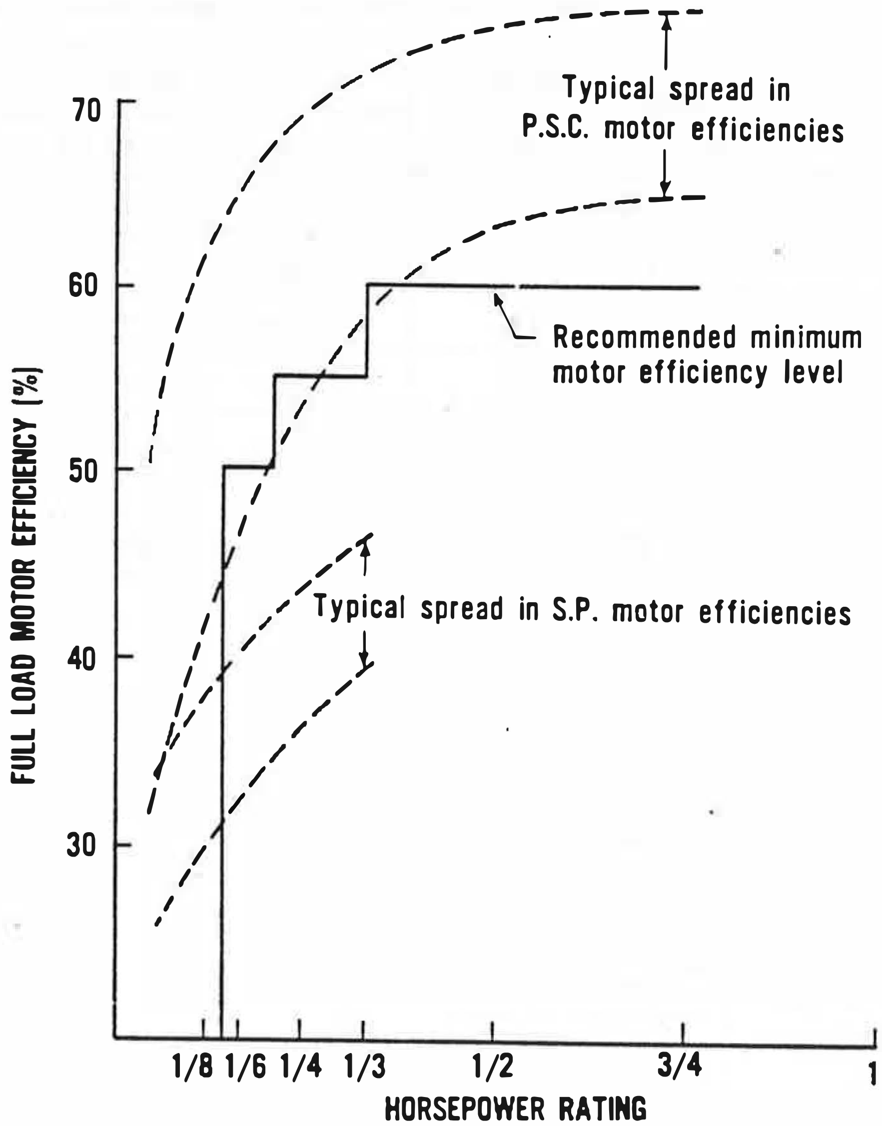


Fig. A.2 Typical P.S.C. and S.P. Motor Efficiencies and Suggested Minimum Motor Efficiency Level (data on typical motor efficiencies supplied by a leading manufacturer of furnace blower motors) (Petersen and Kelly).

Motor*	Rated Power (watts)	Rated Speed	Efficiency at Rated Output
1/3 hp SE motor tested	250	1725 rpm	50.8%
1/3 hp HE motor tested	250	1725 rpm	74.5%
1/3 hp HE motor 2	250	1725 rpm	73.7%
1/3 hp HE motor 3	250	1725 rpm	70.2%
1/4 hp SE motor tested	187	1725 rpm	48.2%
1/4 hp HE motor tested	187	1725 rpm	75.4%

Table A.3 Performance Data of Various Standard and High Efficiency Motors for Belt Drive Blowers (Woods).

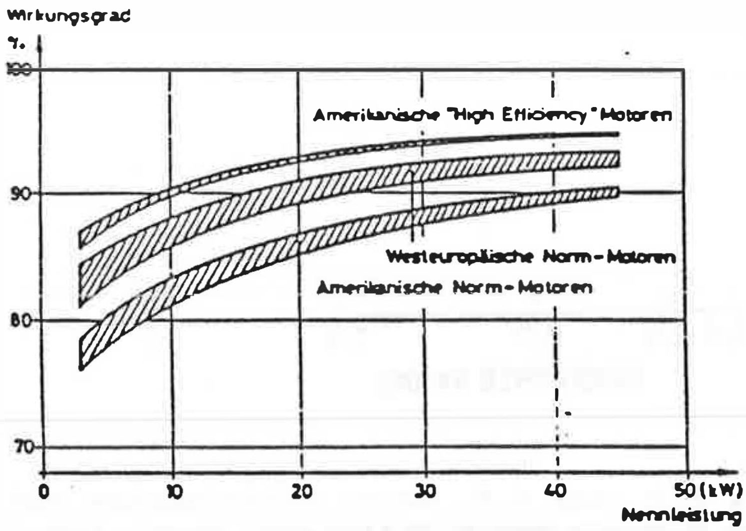


Fig. A.3 Efficiency of U.S. Standard and High-Efficiency and European Standard-Efficiency Motors (Lovins).

Effect of Motor Oversizing on Efficiency

Motors are often oversized by the equipment or fan manufacturer, to avoid call-backs due to system deficiencies in the field. Other reasons are possible increases in imposed load, for example due to the addition of an air conditioning coil, the desire to have as few inventory items irrespective of load to be delivered, and additive "safety factors" for impeller and motor sizing.

Figure A.5 shows the variation of efficiency with percent load for three large three-phase motor sizes. While larger motors have peak efficiencies at 75% load, the figure suggests that, for smaller motors, efficiencies continually decrease a load drops below 100%. This becomes more pronounced for smaller motors. Figure A.1 shows the efficiency performance of 1/3 Hp single phase motors as less than 50% at 100% load. More significant reductions of efficiency occur at lower load percentages. The result is that, if a fractional horsepower motor is consistently run at loads significantly less than the rated load, the ratio of actual efficiency versus peak efficiency can be very low; for example at 20% load, the actual/peak efficiency ratio is 30% or less. For a 1/3 Hp motor with 45% efficiency at 100% load, this would result in efficiencies of 20% or less.

Motors other than synchronous ones will typically increase rotational speed as a result of reduced torque. In other words the slip from synchronous speed is reduced. This increase is usually small in relation to the reduced torque. Clearly, then, there is a non-linear relationship at a variable torque, when no speed control is employed.

Non-linearity especially applies to input current behaviour and input power response, since voltage (without speed control) is almost always constant. As the rotational speed increases (due to torque reduction) the input current can decrease, stay the same or increase. The loss of efficiency with reduced load can be relatively small or large, depending on which motor characteristics are encountered.

The constant input current characteristic is displayed by many smaller, low-efficiency motors. Such motors deliver no input benefits from reduced output requirements. It is the drop in input power with output power reductions, characteristic of some new DC motors, that will best justify their use, instead of better AC motors with no such beneficial characteristic.

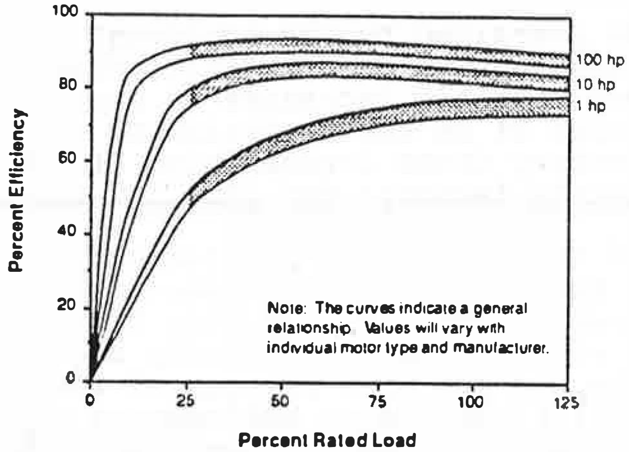


Fig. A.4 Typical Efficiency vs. Load Curves for 1,800 RPM Three-Phase 60 Hz Design B Squirrel Cage Induction Motors (WAPA).

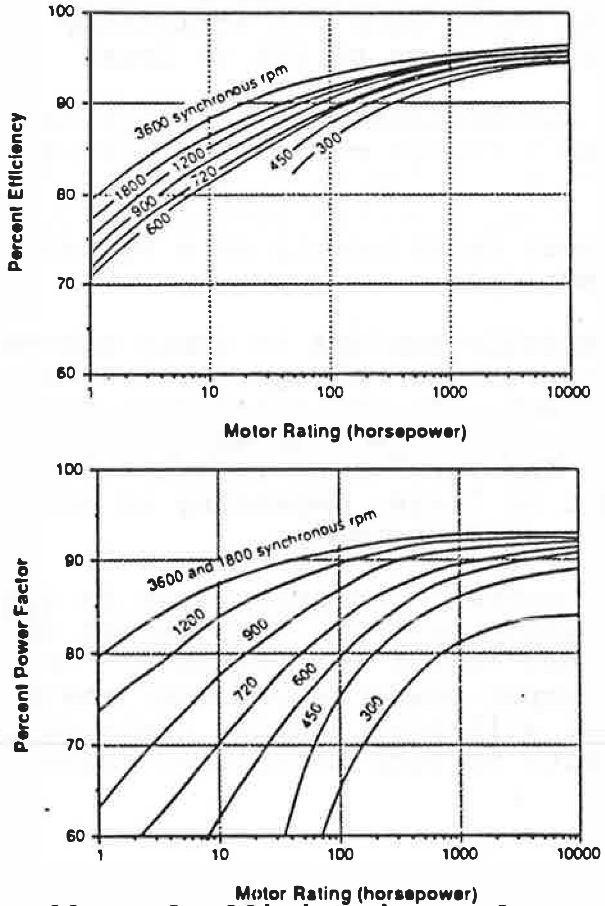


Fig. A.5 Typical Full Load Efficiencies and Power Factors for NEMA Motors with Synchronous Speeds from 300 to 3600 rpm (WAPA).

Effect of Speed on Efficiency

The fundamental (synchronous) speed of an induction motor is fixed by how many pole pairs the design uses. As previously pointed out, synchronous speed equals 3600/(number of pole pairs). Figure A.6 shows the trend of efficiency with reduction in synchronous speed. It suggests that, for fractional HP motors, dropping the speed from 3600 rpm to 900 rpm reduces the efficiency in the order of 10%. By examining the power factor at various speeds in Figure A.6 it is clear why, for fractional Hp motors, 3600 rpm and 1800 rpm are the most common speeds, with 1200 rpm sometimes being used. Motors with slower synchronous speeds should be avoided (except for special applications).

Multi-speed motors (most commonly two-speed) are motors designed to change the number of poles. The speed depends upon which circuit is powered in the motor. Because they have to accommodate additional windings to allow switching of the number of pole pairs, they are physically larger, inherently less efficient due to design issues, and cost significantly more than single-speed motors.

In some cases, it is economic to change output not by speed, but through the use of two properly sized motors, avoiding efficiency reductions due to speed and oversizing. This is useful for applications where significant run times occur at two different operating conditions, for the same equipment.

Power Factor

The parameter, total power required by an induction motor, is the magnitude of the vector addition of active power (that which does work at the shaft and is consumed by motor losses) and reactive power (which maintains the magnetic field).

Total power is the product of the delivered voltage and current, in terms of volt amps, VA). An induction device must have sufficient current available to provide both the active and reactive power. Power factor, is the ratio of active power to total power.

Essentially, the grid supplies power [VA] at a unity power factor to supply active loads at a power factor less than unity. In other words, the grid has to provide I/P.F. times the current to supply the induction motor.

For a conductor to carry the same power, at 50% power factor as at unity power factor would require four times the wire cross-sectional area, since resistive losses are governed by I^2R power considerations. Clearly additional transmission and distribution losses are incurred by low power factors.

Power Factor (Cont.)

Low power factors are important to the utility for a number of reasons:

1. Reactive power is not billable via power and energy meters;
2. Significant reactive power may require upgrading of power lines without financial return to utility [= $1000/kVA];
3. Increased system capacity is required to offset losses, possibly requiring capital cost expenditures [= $500/KW] without a revenue recovery mechanism; and,
4. Voltage regulation is required by the utility, to compensate for reactive power.

Most utilities penalize large users, if the power factor drops below 0.9. Residential customers are ignored, because the utility likely sees the metering and accounting procedures of large numbers of small users not financially or practically worthwhile. However, it is conceivable that, when resistive loads are low, eg. in summer, induction motor power may be as high as 80% of the total consumer load. This could include central air conditioning (compressor, two fans), refrigerator, washer, dryer, continuous ventilation, all possibly using small AC motors with poor power factors. If the average power factor of the motors is 60% and constitutes 70% of the power draw, the total power [VA] required to be provided by the utility is 50% higher than the active (billable) power.

Power Factor (Cont.)

What is less clear is how low power factors affect true input power and energy at the generating plant, as used in the efficiency definition. Discussion in the literature suggests that additional fuel burnt at the plant is limited to additional transmission and distribution losses. From a utility perspective, the user should pay for the effective cost of total power delivered.

Effect of Load and Speed on Power Factor

Trends similar to that discussed for efficiency versus percentage load occur for power factor performance (Fig. A.7). Small motors can experience significant power factor reductions, for example, a drop of 0.25 or more when the load drops from 100% to 40%.

It should also be noted that the speed of the motor can significantly reduce the power factor (see Fig. A.6). Using a 1200 rpm instead of a 3600 rpm fractional Hp motor can decrease the power factor by 10% to 20%, depending on the motor size.

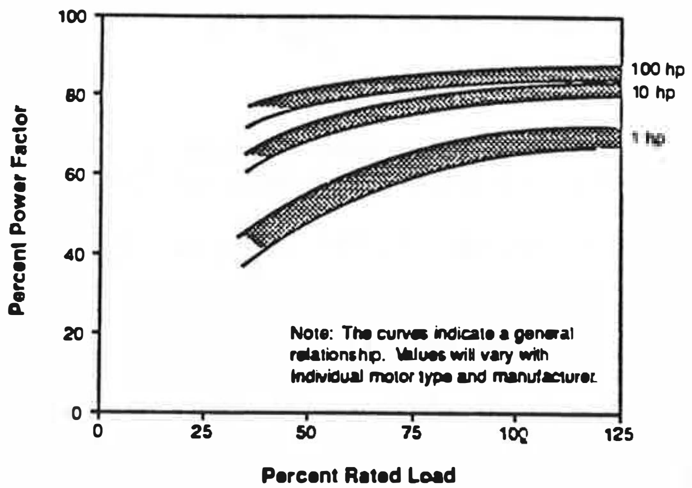


Fig. A.6 Typical Power Factor Vs. Load Curves (WAPA).

Effect of Power Factor on Efficiency

There is additional power consumption due to grid losses at the generating plant equivalent to 8% of active power, at a grid power factor of 0.9. For the purpose of our study, the following methodology is suggested to fairly compare the impact of low and high power factors. If one assumes that, for low power factors, the grid losses vary as the square of total current:

$$\textit{Power lost from grid} = I^2R \quad (R \textit{ is grid resistance})$$

$$= 0.08\ P_A\ @\ 0.9\ PF$$

$$\textit{Power factor } (PF) = \frac{P_A}{P_T} = \frac{I_A}{I_T}$$

$$\textit{Total Input Power} = P_A + \textit{Grid Loss} = P_A + 0.34\left(\frac{1}{(PF)^2} - 1\right)P_A$$

$$\textit{Total Input Power} = \left(0.66 + \frac{0.34}{PF^2}\right)P_A$$

If one further assumes that a motor is responsible for its share of grid losses at an average grid loading (i.e. at 0.9 power factor), its grid losses at different power factors would be expressed:

$$\textit{Grid Loss} = 0.065\left(\frac{1}{PF^2}\right)P_A$$

Where grid losses are 0.08 P_A at a power factor of 0.9, the increase in grid losses due to power factors of less than 1.0 is:

$$\textit{Grid Loss Increase} = 0.065\left(\frac{1}{PF^2} - 1\right)P_A$$

The total power at the plant is the active power at the house, P_A, plus the grid loss due to P_A (0.065 P_A), plus the grid loss due to a power factor less than unity.. It can be argued that power consumed based on P_A, that is (P_A + 0.065 P_A), is billed by the utility in its rate structure, even though only P_A is metered.

Effect of Power Factor on Efficiency (Cont.)

The ratio of actual power consumed to power consumed at a power factor of 1.0 is:

$$R = \frac{P_A + 0.065\ (\frac{1}{PF^2})\ P_A}{P_A + 0.065\ P_A} = (0.94 + \frac{0.06}{PF^2})$$

Therefore, the effect of power factor expressed in terms of efficiency reduction (i.e. increase in relative input power is 1/R):

$$\epsilon_{pf} = \frac{1}{0.94 + 0.06/PF^2}$$

While this methodology is more applicable to input power provided at the generating station, it is assumed that this efficiency reduction factor is applicable to a proportional power increase at the house.

This would result in the following modified efficiencies for a conventional 1/3 Hp motor:

	Power Factor	Conventional Efficiency	PF-modified Efficiency
100% Load	0.8	45%	43.5%
40 % Load	0.6	20%	18.0%

AC Motor Speed Controls

Table A.4 gives an overview of the variety of automatic adjustable speed control technologies complete with comments and horsepower range applicability. DC motor speed control will be discussed in the section on Electronically Commutated Motors. From this information, it can be seen that the control strategies that can be used for fractional Hp motors are multi-speed motors (previously discussed), eddy-current drives and electronic adjustable speed drives of the voltage-source inverter type.

An eddy current drive is based on magnetic clutch that can vary the amount of slip between the motor shaft and the output shaft. Output speed is controlled by a low-power, solid-state controller that varies the magnetic field.

Maintaining the magnetic field consumes about 2% of the rated drive power, essentially equivalent to the motor's shaft power.

	Technology		Applicability (R = Retrofit; N = New)	Cost	Comments
Motors	Multispeed (incl. PAM[1]) Motors		Fractional-500 hp PAM: fractional-2,000+ hp R,N	1.5 to 2 times the price of single-speed motors	Larger and less efficient than 1-speed motors. PAM more promising than multi-winding. Limited number of available speeds.
Motors	Direct-Current Motors		Fractional-10,000 hp N	Higher than AC induction motors	Easy speed control. More maintenance required.
Shaft-Applied Drives (on Motor Output)	Mechanical	Variable-Ratio Belts	5–125 hp N	$350–$50[2]/hp (for 5–125 hp)	High efficiency at part load. 3:1 speed range limitation. Requires good maintenance for long life.
Shaft-Applied Drives (on Motor Output)	Mechanical	Friction Dry Disks	Up to 5 hp N	$500–$300/hp	10:1 speed range. Maintenance required.
Shaft-Applied Drives (on Motor Output)	Eddy-Current Drive		Fractional-2,000+ hp N	$900–$63/hp (for 1 to 150 hp)	Reliable in clean areas. Relatively long life. Low efficiency below 50% speed.
Shaft-Applied Drives (on Motor Output)	Hydraulic Drive		5–10,000 hp N	Large variation	5:1 speed range. Low efficiency below 50% speed.
Wiring-Applied Drives (on Motor Input)	Electronic Adjustable Speed Drives	Voltage-Source Inverter	Fractional-1,000 hp R,N	$1500–$80/hp (for 1 to 300 hp)	Multi-motor capability. Can generally use existing motor. PWM[3] appears most promising.
Wiring-Applied Drives (on Motor Input)	Electronic Adjustable Speed Drives	Current-Source Inverter	100–100,000 hp R,N	$200–$30/hp (for 100 to 20,000 hp)	Larger and heavier than VSI. Industrial applications, including large synchronous motors.
Wiring-Applied Drives (on Motor Input)	Electronic Adjustable Speed Drives	Others	Fractional-100,000 R,N	Large variation	Includes cycloconverters, wound rotor, and variable voltage. Generally for special industrial applications.

[1]PAM means Pole Amplitude Modulated. [2]The prices are listed from high to low to correspond with the power rating, which is listed from low to high. Thus, the lower the power rating, the higher the cost per horsepower. [3]PWM means Pulse Width Modulation.

Table A.4 Adjustable-Speed Motor Drive Technologies (WAPA).

AC Motor Speed Controls (Cont.)

This value would be constant independent of imposed load. For a 250 W motor shaft power, this consumption would be 5 W. Of the 250 W at 100% speed it would transmit 98% or 245 W, while at 50% speed it would transmit 48% or 120 W.

The losses are in the form of heat and fractional Hp drives (1/4 Hp and up) are typically air-cooled. Eddy current drives are large, about twice the size of the motor, and are being replaced by electronic Adjustable Speed Drive (ASD). Eddy drives have an advantage of not producing significant harmonics or voltage transients compared to electronic Adjustable Speed Drives (ASD).

Inverter-based electronic ASD's are by far the most common type and are being used with fractional horsepower motors in residential appliances. The principle of operation is rooted in the fact that motor speed is proportional to the frequency of the AC waveform. An inverter-based ASD converts 60 Hz AC into DC power and reinverts it to a frequency-adjustable and voltage-adjustable AC waveform. The frequency usually ranges from 0-120 Hz but can go as high as 180 Hz.

AC Motor Speed Controls (Cont.)

A voltage-source inverter (VSI) Adjustable Speed Drive, most common for fractional Hp motors, produces a square waveform rather than a simulated sinusoidal one. A VSI can operate several motors at once.

Because ASD's are more compact than mechanical speed controls and do not have to be mechanically coupled, they can easily be retrofitted or located, for example, in the control box of a HRV.

The typical efficiencies of ASD's are shown in Figure A.8. Constant torque ASD's have flatter efficiency curves, but are more expensive. Very likely residential ASD's are of the variable torque variety, which exhibit efficiencies of 95% at 100% speed and 85% at 40% speed. This means motor efficiency is reduced slightly, but the potential of reducing input power, by reducing output due to speed reduction, exist in many applications. The effect of using a Adjustable Speed Drive, on motor loading and the resulting motor efficiency, needs to be explored, as does the effect of speed changes on fan efficiency.

In regards to the effect of Adjustable Speed Drives on motor efficiency, Competitek sm (now E Source) makes the following two points:

1. ASD's have an efficiency less than 100%, therefore the motor/ASD combination, run at or near the rated speed, consumes more energy; and

2. For the same loading, the motor efficiency will be lower at lower frequencies (speed) than at the design frequency.

Figure A.9 suggests that, at 100% speed the ASD has reduced the efficiencies to 77% and 82%, for standard and high efficiency motors, which were about 85% and 90% respectively (on a 10 Hp motor).

Manual adjustable speed controls include the familiar belt/pulley drive of furnace fans (discussed in "Drive Transmission Losses") and friction dry discs.

Friction dry discs allow a wide range of speed ratios, but are considered expensive. Speed is varied manually, via a crank, by changing the transmission ratio. They are 95% efficient, but require more maintenance, are more bulky and are less flexible than electronic ASD's.

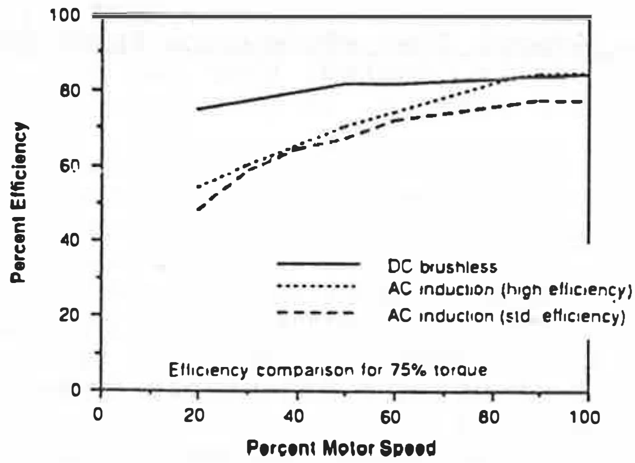


Fig. A.7 Typical Efficiency Curves for an AC Inverter Drive (WAPA).

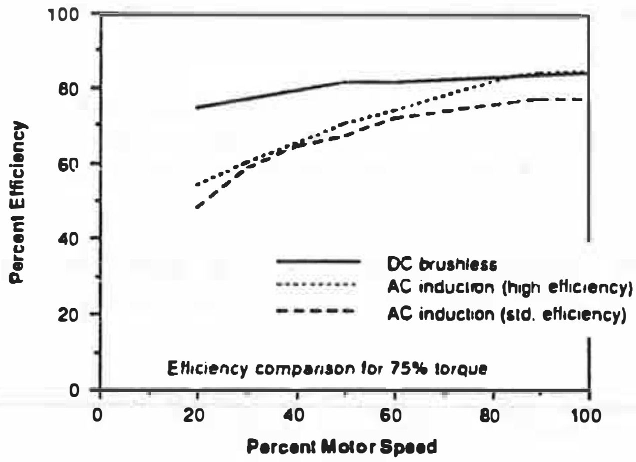


Fig. A.8 Compared Efficiencies of 10-Hp AC Induction Motors with ASD and Brushless DC Motors as a Function of Speed (WAPA).

DC Motors

DC motors are often used where speed control is required, since varying the voltage varies the speed. Electricity is supplied to the rotor windings via a ring of electrically isolated copper bars, known as a commutator. Conventional DC rotors require brushes, causing wear on both brushes and commutator, and are expensive to manufacture.

In more conventional designs, the stator can be either a winding or a permanent magnet, producing a magnetic field. However a more important permanent magnet [PM] motor is one that has windings in the stator generating a rotating magnetic field and a PM rotor. The speed of the motor is then the speed of the rotating field. Because there are no losses in the "brushless" rotor, these motors are more efficient than induction motors. This type of motor is known as an electronically commutated motor (ECM), see Figure A.10. Essentially the brushes of a conventional commutator are replaced by an integrated circuit which switches polarity to the windings of the stator in synchronization with the moving field of the rotor. It then becomes simple to control speed by controlling the frequency of the switching.

Figure A.8 shows the comparison of a 10 Hp ECM motor to standard and high-efficiency, ASD-controlled induction motors. At low speed there is a dramatic increase in efficiency. Since the magnetic field is provided by permanent magnets, little reactive power is consumed, allowing for power factors close to unity.

There is accelerated work being done on inverter drives and custom integrated chips, mostly in Japan, but also in North America, with a view to application in the residential market. General Electric offers Integrated Commutated Motors (ICM), in the fractional horsepower range [to 1.5 Hp] which provide more sophisticated switching capability. By adding programmability to the control, through the use of computer technology (EEPROM), motor controls can be customized for specific applications. In other words, speed can be controlled using a number of inputs or sensing devices that determine the equipment output characteristics.

One application of the technology is the use of two ECM motors for air handling in a top-line Carrier gas furnace (see "PM Motors in Residential Applications", Fig. A.11). It should be noted that some ECMs create electronic "noise" which causes some problems for both utilities and consumers, the latter when it affects other household devices.

ECM motor efficiencies in 1/3 Hp to 1/4 Hp range are rated at around 78%. A high efficiency 1/4 Hp AC induction motor would have an efficiency of 71% to 74% but this is reduced to about 65% to 70% with electronic ASD's.

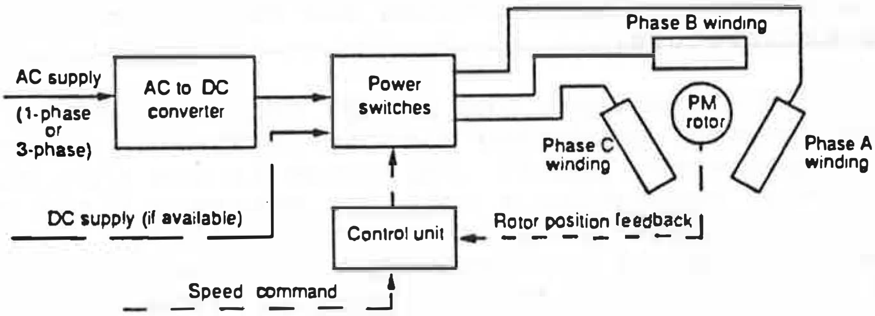


Fig. A.9 Schematic of Electronically Commutated Permanent-Magnet (PM) Motor (WAPA).

PM Motors in Residential Appliances

An ever-increasing number of residential appliances use PM motors. A particularly innovative example is the Carrier Weathermaker SXi gas-fired, forced-air furnace (also sold under the Bryant, Day and Night, and Payne brand names). Like many top-of-the-line furnaces, it uses a condensing heat exchanger for high thermal efficiency, and an induced-draft exhaust blower to vent the flue gases. Unlike most others, this furnace is also electrically efficient, due to the use of two electronically commutated motors: one for the main ventilation fan, the other for the induced-draft blower.

The burner operates in two stages, allowing the furnace to operate at low output for most of the required heating hours. The corresponding low speed of the main fan results in a power consumption of less than 100 W, compared to 600–1,000 W in a typical furnace. The low-speed capabilities, combined with sophisticated controls, also bring increased comfort and reduced noise. The installed cost of the furnace is about $2,500, roughly $300 to $700 more than other condensing furnaces (Nisson 1988).

Fig. A.10 Furnace Fan Application of ECM Technology (WAPA).

Drive Transmission Loss

It usually assumed that a direct drive arrangement has a power motor transmission loss of zero, assuming the motor is not in the airstream. Due to space limitations, the motor is often mounted directly in the intake orifice of the fan. This can cause significant aerodynamic resistance to flow, resulting in lower efficiencies.

The amount of obstruction is dependant on the exact detail (aerodynamics of motor housing, free area around motor, degree of recess in orifice). Inferring from manufacturers test data, the effective drive efficiency, ε_d, ranges from 84 - 95%. (Ariewtz) suggests, however, that the efficiency reduction of forward-curved centrifugal, from a possible 60%, to a tested 35%, is due in large measure to the (large) motor being in the airstream.

Belt drives also experience losses in output power prior to transmitting torque to the driven equipment. If smaller and more efficient motors are designed into the inlets of fans, and are streamlined, this reduction in system efficiency could be radically reduced.

V-belt drive losses can be characterized by the A.M.C.A. formula for fractional horsepower motor applications:

$$L_d = 9.4 - 4.65 \ln P_m$$

where L_d = drive loss in percent of motor output
P_m = motor output power, Hp

Efficiency of drive, ε_d, would equal $[1-L_d]$. It should be noted that, for example, a 1/3 Hp motor would experience a drive loss of 14.5%.

A study done by ORTECH found that conventional belts (normal tension) experience losses closer to 10% for a 1/3 Hp motor. By loosening the belt this figure could be reduced to 2% - 6%. Using a cog v-belt can reduce the losses roughly by half, while the use of a synchronous belt all but eliminated this drive loss.

This report also studied the effect of fan sleeve bearings versus ball bearings, on drive loss of belt-drive systems. With ball bearings, the required fan input power dropped by 10%. If ball bearings have an efficiency, E_b, of 99%, then the sleeve bearing loss would be about 89%.

Note that, if the fan wheel is supported only by the motor shaft, the motor may reduce in efficiency due to the increased bearing load.

Drive Transmission Loss (Cont.)

It should be noted that system interactions tend to reduce power savings. The 10% reduction in fan power due to ball bearings reduced input power only by 5%, since the fan/motor combination was able to run at a slightly higher rpm, incurring a higher power draw. If an electronic speed drive had been used to recreate the conditions of the system with sleeve bearings, the 10% saving could have been realized, but the efficiency of the speed drive would need to be taken into account.

Motor efficiency is also reduced when the motor shaft bearing supports the weight of the impeller, in a direct-drive configuration. This is a major effect with sleave bearings and a minor one with ball bearings (doubling a 1% loss gives 2%, but doubling an 11% loss gives 22%).

APPENDIX B: FACTORS AFFECTING THE EFFICIENCY OF SMALL AND LARGE BLOWERS

APPENDIX B: FACTORS AFFECTING THE EFFICIENCIES OF SMALL AND LARGE BLOWERS

Table B.2 shows a survey of forward-curved furnace fans ranging from 43% to 57% efficiency. Table B.3 shows that an improved version can operate at 62% efficiency. Backward inclined impellers can often increase efficiencies by 20%. For additional design effects see Table B.4.

The blowers used in domestic furnaces typically have rated peak efficiencies between 40% and 50%, depending on whether tight or standard housings are used. However, larger blowers (for the industrial sector) are available with efficiencies of 80% (Table B.1). Unfortunately there is a scarcity of published information on the factors which contribute to the efficiency difference between the two sizes of blowers. Using the available information, this section will address the possible factors which contribute to the differences in efficiency.

In addressing the different efficiencies, it is useful to first look at the range of efficiencies available for various blower configurations. Table B.1 shows the efficiencies of a sampling of blower configurations. The efficiencies represent the peak efficiencies from the performance data provided by blower manufacturers.

The data in Table B.1 suggests that the improvement in efficiency from a domestic furnace blower to an industrial blower has two sources; the benefits of larger scale (accounting for 10-20 percentage points) and blade design (≈ 10 percentage points increase with backward-curved wheels).

Due to a lack of physical data on the blowers, it is not possible to quantitatively assess the impact of specific scaling factors

Efficiency	Blower Configuration
80%	Backward Curved Wheel (1650 mm dia.)
70%	Backward Curved Wheel (300 mm dia.), or Forward Curved Wheel (900 mm dia.)
60%	Forward Curved Wheel (300 mm dia.)
50%	Forward Curved Wheel (250 mm dia., direct drive)
40%	Forward Curved Wheel (225 mm dia., tight housing), or Forward Curved Wheel (225 mm dia., standard housing, with belt drive losses)

Table B.1 Typical Efficiencies of Various Blower Configurations.

Table 1 - Peak Blower Efficiencies Within Manufacturer's Recommended Range						
Manufacturer	Wheel Length (in.) *	Standard Blower Housings		Tight Blower Housings	
		belt drive	direct drive	belt drive	direct drive
Lau	9.5	55%	46%	44.6%	N/A
Lau	8	53.8%	50%	42.8%	N/A
Lau	7.12	54.7%	52%	48%	N/A
Air Vector	9.5	N/A	53%	N/A	44%
Air Vector	8	N/A	53%	N/A	42%
Air Vector	7.12	N/A	57%	N/A	43%

Table B.2 Peak Blower Efficiencies Within Manufacturer's Recommendations (Woods).

Table 3 - Alternative Blower Designs With Efficiency Improvements			
Type of Blower	Manufacturer	Description	Peak Efficiency
plastic, backward inclined	M.K. Plastics (Montreal)	wheel dia.= 10.5 in. wheel length = 8-1/16"	65%
metal - forward curved (Fergas wheel)	Beckett Air (Ohio)	wheel diameters only up to 4.75"	claims to improve efficiency from 57% to 62%

Table B.3 Alternative Blower Designs With Efficiency Improvements (Woods).

on efficiency. However, three probable factors are addressed qualitatively below (see also Table B.4).

1. Clearance at Blower Inlet

There will be an optimum clearance between a blower housing and the wheel as there is a trade-off between flow leakage and viscous losses. The gap creates a flow leakage path which decreases the blower efficiency. However, decreasing the gap also increases the viscous losses caused by the relative motion of the wheel and housing. In general, the optimum efficiency will occur at very small clearances.

Neise showed that the efficiency of a backward-curved blower increased from 60% to 70% by tightening the inlet clearance from 10 mm to 1 mm. However, Wright showed that decreasing the inlet gap from 1.6 mm to 0.33 mm increased the efficiency by about three percentage points. It should be noted that both of these papers reported on results with backward-curved blowers. Since forward-curved blowers operate with less of a static pressure rise, the leakage losses will be than with the backward curved blowers with the same inlet gap. Furthermore, the actual improvement potential from tightening the inlet clearance will depend on the typical clearances on existing blowers.

2. Clearance at Blower Cut-Off

The cut-off of a blower is the part of the housing near the inlet which directs the air out of the blower, away from the rotating wheel. Similarly to the inlet clearance, the cut-off clearance balances the viscous losses against the leakage losses. Smith, O'Malley, and Phelp have shown that the efficiency of a backward-curved blower can increase from 75% to 82% by <u>increasing</u> the cut-off ratio (cut-off clearance/wheel diameter) from 3% to 8%. Again, the actual potential for improvement will depend on the typical cut-off ratios on existing blowers.

3. Relative Roughness of Wheel Blade

The friction losses in the air passing through the blower wheel will depend on the relative roughness in the blade passage. The relative roughness is the ratio of the surface roughness to the size of the blade passage. Since the materials, and thus absolute roughness, are similar for large and small blowers, the relative roughness will be higher for the small blowers.

The relative roughness of smaller blower wheels could be reduced using coatings (such as epoxy or teflon) which would add $15 to $30 to the cost of the wheel (the cost estimate was supplied by a coating shop). Some coatings could also improve the longer term performance of blowers by resisting the build-up of dust on the blower wheel.

Design Parameter	Impact on Efficiency	Comments
Blade Design		
- outlet blade angle	- backward curved blades could increase efficiency by up to 20%	- in general, blowers with backward curved blades provide the flow rates at higher static pressures (however, Westinghouse developed a blower which may be suitable)
- number of blades		- more blades increase skin friction losses but decrease eddy current losses
- chord of blade (or radial depth)	- doubling the length of the blade could increase the efficiency by 20%	- for similar flow, both power and speed decrease as blade depth is increased
Bearings	- 15-34 watts can be saved by using ball bearings instead of sleeve (increase in efficiency of 4-8%)	- no increase in sound level measured with ball bearings
Casing Design		
- size of casing	- a wheel will have an optimum casing size, deviation from which could degrade efficiency by up to 16%	
- inlet vanes	- efficiency not greatly effected by inlet vanes	- positive pre-rotation provided by inlet vanes will change static head and power in proportion
- outlet diffuser guide vanes	- guide vanes will increase efficiency by reducing shock and eddy losses	- if flow varies from design conditions, then vanes may increase losses (mainly used in high pressure blowers)
- clearance between inlet nozzle and impeller eye	- with a backward curved blade, the efficiency can be increased by 10% by tightening the clearance from 10 to 1 mm.	
Cut-Off Design		
- clearance to impeller	- deviation from the optimum cut-off clearance can reduce efficiency by up to 7%	
- location of cut-off	- efficiency can drop off by 4% with 25% of wheel diameter exposed	
- slope of cut-off		- sloping the cut-off reduces noise and therefore should improve efficiency
Type of Drive		
-direct drive vs belt drive	- for the same impeller wheel and housing, direct drive can be up to 9% less efficient	- direct drive blowers have lower costs and fewer installation problems (eg. poor tensioning of belts, or poor quality of pulleys) - efficiency of direct drive blowers could increase if motor was somewhat removed from blower inlet
Wheel, or Impeller Design		
- length/diameter ratio	- the ratio can effect the efficiency by up to 6%	- there may be an optimum length/diameter ratio for each wheel diameter
- material used		- plastic wheels are lighter and therefore put less loading on motor bearings (for direct drive)
Material Roughness	- at similar flow conditions, pump efficiency increases by 3% when a surface roughness of 0.005 inches is polished	- at low fan Reynolds numbers, the fan efficiency can drop by up to 10%, therefore coatings could help to minimize the relative roughness and minimize the change in efficiency - may present potential for plastic coatings

Table B.4 The Effect of Various Blower Design Parameters on Efficiency (Woods).

In general, the information currently available suggests that it is unlikely that a blower could be produced for furnaces with an efficiency of 80% (the efficiency of a larger backward-curved blower). Based on the information available, the efficiency of a high efficiency furnace blower is more likely to be 70% to 75%.

In addition to the above three factors, the number and size of blades may vary somewhat from the smaller to larger blowers. In general, increasing the number of blades makes the blade passage smaller. The smaller blade passage reduces the secondary flows in the blade passage and improves the efficiency. However, increasing the number of blades also increases the total surface area, which in turn increases the skin friction losses on the blades. The significance of either the secondary flow losses or skin friction could change as the blower size is increased.

APPENDIX C: FAN SYSTEM INTERACTION EFFECTS

APPENDIX C FAN SYSTEM INTERACTION EFFECTS

Figure C.1 shows the various characteristics for a large backward-curved blower. The figure shows the following parameters as a function to flow rate:

TP =	total pressure	SP =	static pressure
TE =	total efficiency	TS =	static efficiency
BHP =	input brake horsepower		

There are a number of characteristics worth noting:

1. Maximum static efficiency of 86% occurs at 55% of free flow (i.e. free flow being at zero static pressure).

2. Maximum total efficiency of 89% occurs at 59% of free flow.

3. At free flow, total efficiency is still 30%, due to the power equivalent of the dynamic head, though static efficiency is zero.

4. Maximum input power occurs at 67% of free flow, where static efficiency is 80%, or 0.93 of the maximum efficiency.

5. At peak efficiency (55% of free flow), the dynamic head is 5% of the total pressure; at 75% of free flow and 60% of the static pressure, the dynamic head is 13% of the total pressure.

Summarizing, the air flow, static pressure, and efficiency performance:

% Free Flow	% Maximum Static Pressure	% Peak Output Power	ε	% Input Power at Peak Efficiency
55	95	100	86	100
65	73	91	80	105
75	59	85	71	101
85	34	55	48	93

The fan performance requirement is often specified at a higher static for a given design flow rate, to take into account the maximum static experienced in the field, so as to minimize callbacks. If the static encountered is relatively lower, the fan becomes "oversized" and the fan performance must necessarily follow the fan curve, downward, to the right of the peak efficiency, if there is no change in fan speed (rpm). For example, if the actual site conditions allow it to move away from the design point (55% free flow, 95% maximum static pressure), the application "oversizing" reduces the efficiency from 86% to 71%. Since the input power curve is relatively flat, no energy savings are available due to the reduced power output (assuming no change in rpm).

Figure C.2 demonstrates conventional engineering specification based on static pressure/flow performance independent of efficiency considerations. With the superimposed efficiency curve in Figure C.2, it can be seen that the upper limit of the recommended selection range is actually at the peak efficiency while the lower limit corresponds to an efficiency value of about one-third the peak efficiency.

Figure C.3 shows the fan performance of a forward-curved centrifugal blower that is of a similar capacity to that used in furnace fans.

If the design operating point for the fan is just right of the maximum static efficiency (at 2600 rpm), then:

Air Flow	550 L/s
Static Pressure	480 Pa
Output	264 W
Input	1650 W
ε	16%

If the fan is installed, in an application with a significantly lower system static/flow (i.e. "oversized"), the following parameters result:

Air Flow	675 L/s
Static Pressure	240 Pa
Output	162 W
Input	1620 W
ε	10%

To begin with, the 162 W output could be supplied with 40% less input power [1000 W vs. 1620 W], with a different fan whose peak static efficiency of 16% coincides with second operating condition, above.

If 550 L/s is the desirable air flow, the same fan can be run at 80% of the fan speed of 2150 rpm. This results in the following characteristics:

Air Flow	550 L/s
Static Pressure	175 Pa
Output	96 W
Input	960 W
ε	10%

At this lower fan speed the design air flow intersects the fan curve at the right of the peak operating point resulting in a reduced static efficiency of 10%. This also saves 40% of the original 1620 W input power.

Clearly, if a fan with a higher peak efficiency (either by operating closer to the peak efficiency or utilizing a fundamentally better fan design, or both) significant reductions of input power can be achieved. A 70% efficient fan, designed for peak operation at 550 L/s and 175 Pa would require an input power of 140 W. This would result in a reduction of over 90% when compared to an inefficient, over-sized fan.

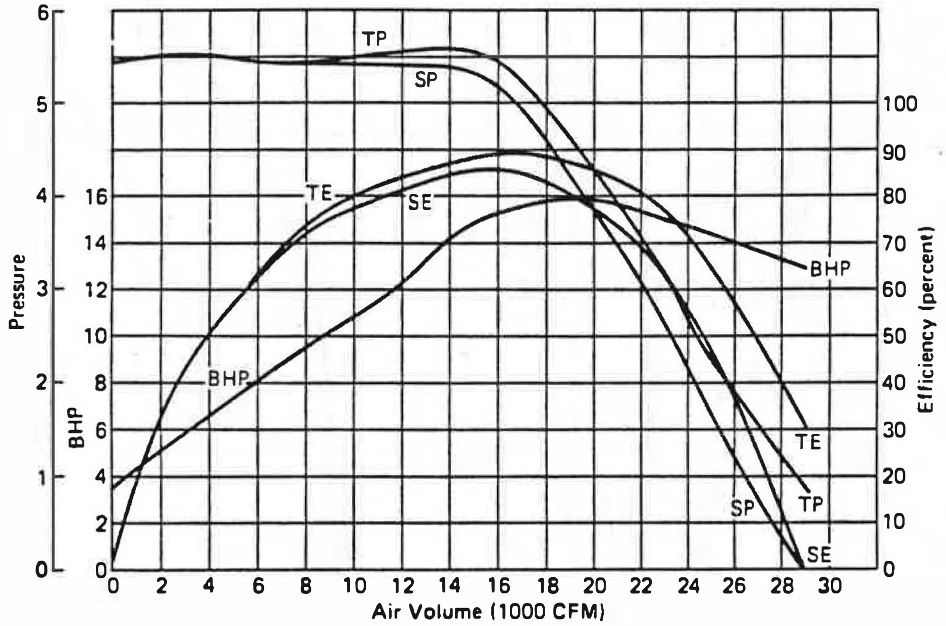


Fig. C.1 Sample Performance Curve (Clifford, pg. 747).
Note: TP = total pressure, SP = static pressure,
TE = total efficiency, SE = static efficiency,
BHP = brake horsepower

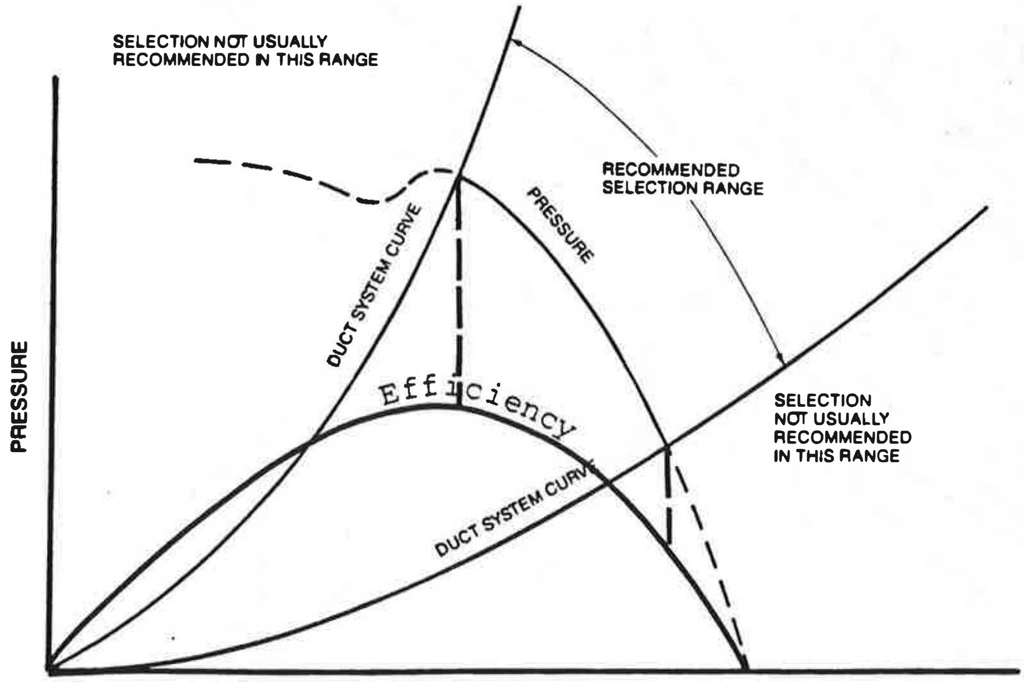


Fig. C.2 Recommended Performance Range of a Typical Centrifugal Fan (A.M.C.A.).

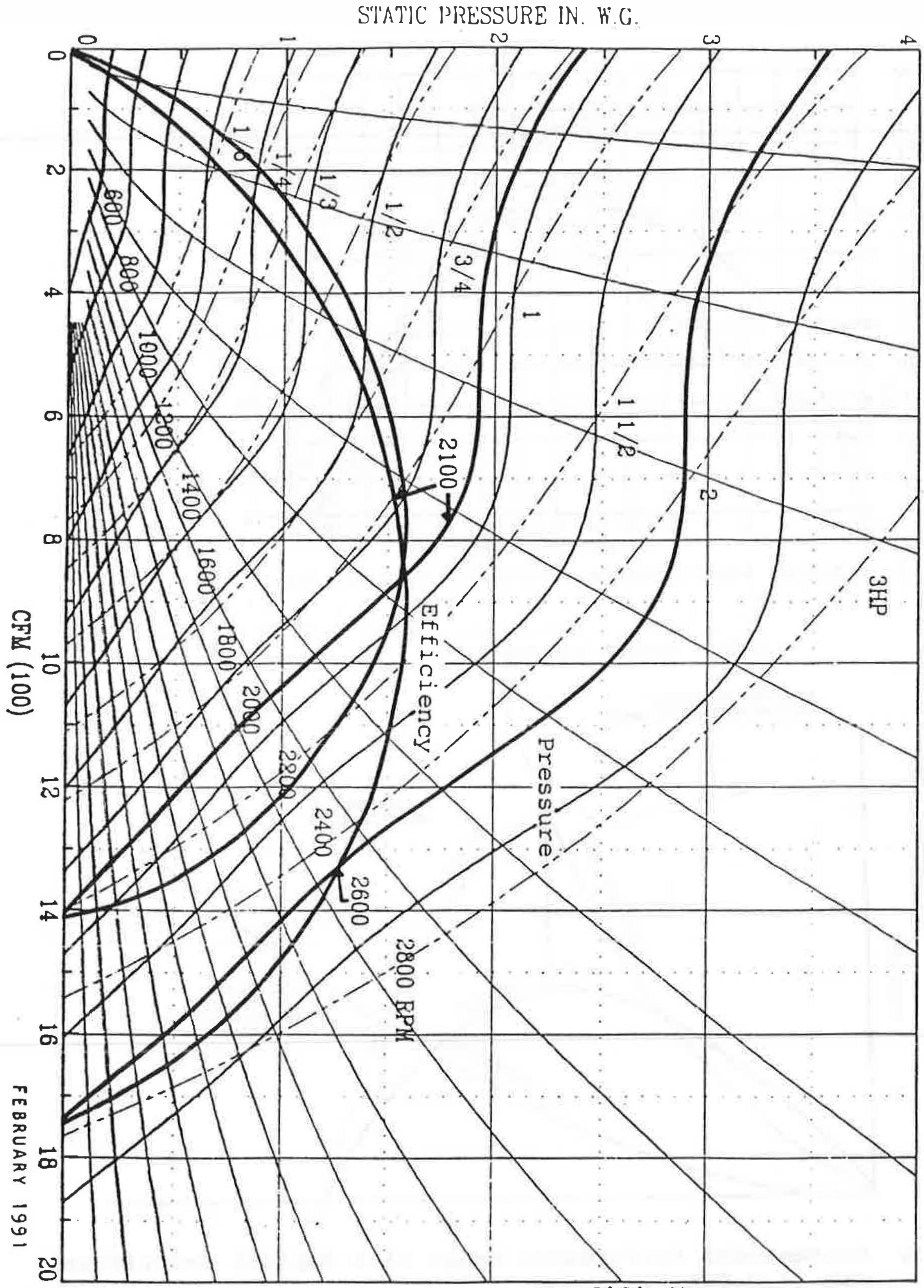


Fig. C.3 Manufacturer's Fan Curve (modified)

Figure C.4 demonstrates a much more efficient fan, run at high rpm and capable of producing relatively high static pressure. The static efficiency behaviour is presented for 6000 rpm and 7000 rpm.

At the higher speed the fan maintains its efficiency over a larger range with respect to the free flow. If we examine the static efficiency performance above 65% we obtain the following characteristics:

	6000 rpm	**7000 rpm**
Free Flow	650 cfm	750 cfm
Minimum % Free Flow @ $\varepsilon = 0.65$	40%	37%
Maximum % Free Flow @ $\varepsilon = 0.65$	75%	83%

Therefore, this fan at 7000 rpm, maintains efficiencies of 65% over 40% of the full range of air flows and static pressures.

System Curves

Figure C.5 shows a typical fan/system interaction curve.

Differences between Fan A and B could emanate from:

1. The same fan run at different speed;
2. A different size fans run at same or different speed; or
3. A different fan design.

If the external system (usually connected ductwork) can be characterized by the curve of the form;

$$P_s = kQ^x$$

P_s = static pressure loss
Q = volumetric air flow
k = system constant
x = flow characteristic exponent (usually between 1 and 2)

the system curves such as shown in Figure C.5 can be derived.

For the conditions shown, using system A and changing from fan A to fan B (eg. by a speed change) increases both the static and the flow. For the same fan, changing system A to system B, which is a system with higher relative static, reduces the flow. Alternatively, if we are interested in the same flow, eg. for equipment reasons, but the external static is higher, the higher capacity fan, fan B would have to be used.

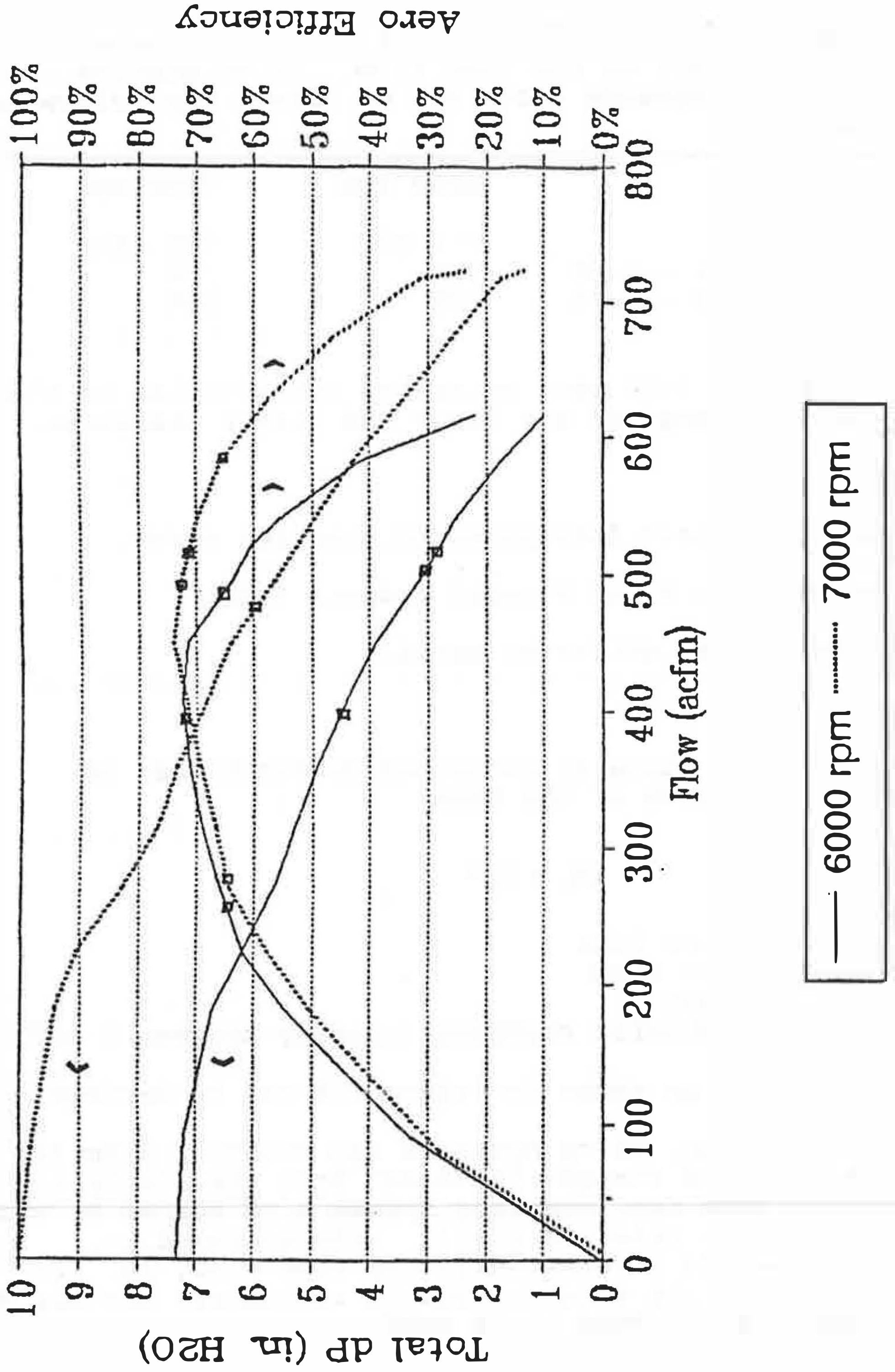


Fig. C.4 Manufacturer's Fan Curve.

These changes affect the input power required by the fan. It is important to realize that, while air flow for a given fan is proportional to fan speed, N [rpm]:

$$Q_2 = Q_1\left(\frac{N_2}{N_1}\right)$$

the fan power input rises and falls by the cube of the speed:

$$P_2 = P_1\left(\frac{N_2}{N_1}\right)^3$$

Various motor designs react differently when challenged with reduced torques, as compared to what happens at the design operating point. Almost all motors, except synchronous ones, will increase rotational speed as a result of reduced torque. When the torque drops off, and the rotational speed increases some, the input current of motors connected to fans can: drop off; stay essentially constant; actually increase, sometimes in direct proportion to increases in rotational speed. This third characteristic results in increases in input power as output power is decreased. As a result, off-design efficiencies can drop significantly.

Let us assume that we have a fan with the lower performance curve in Figure C.6. Due to a fan efficiency improvement the fan input power has been reduced by 40% to the lower power curve marked H. (This is an increase in fan efficiency from an assumed 40% to 67%). The motor responded to the "unloading" due to the efficiency improvement by increasing speed by 10% and performance moved from point 1 to point 2 on the system curve. This resulted in the following:

1. A 10% higher air flow, not required.
2. A 33% higher input power supply than at the design air flow.

Let us also assume that before the efficiency improvement, the motor had a 90% loading at an efficiency of 50%. The following table shows that the 40% improvement in fan input power at the design flow resulted in only an 12% reduction in motor input power:

	Flow [%]	Load [%]	ε_m [%]	ε_f [%]	Input Power [%]
Before Improvement	100	90	50	40	100
After Improvement	110	72	45	67	88
W/ Speed Reduction	100	54	40	67	75
Resizing Motor	100	90	50	67	60
High Eff. Motor	100	90	80	67	38

By maintaining air flow at the desired level, savings can be increased to 25%. By properly sizing a new standard efficiency motor (50% efficiency at 90% load) the full 40% savings can be realized. Further improving the efficiency of the motor from 50% to 80% at 90% load **increases the savings to 62%**.

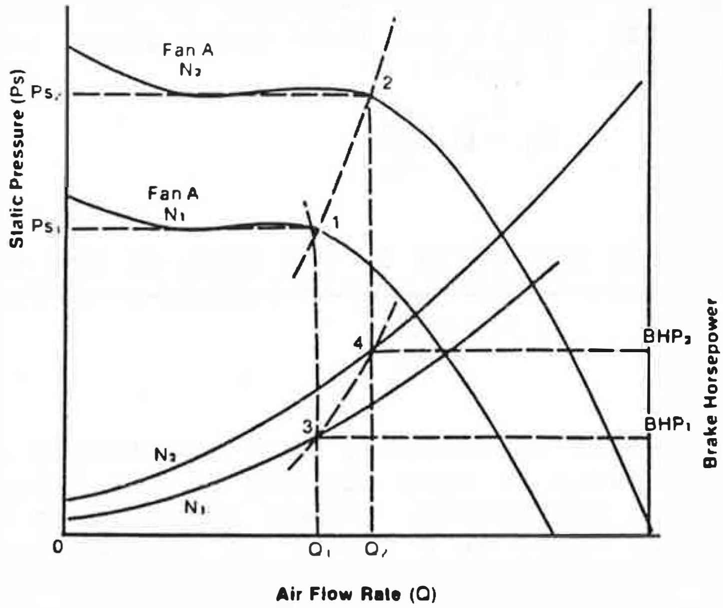


Fig. C.5 System and Fan Interaction (Torin).

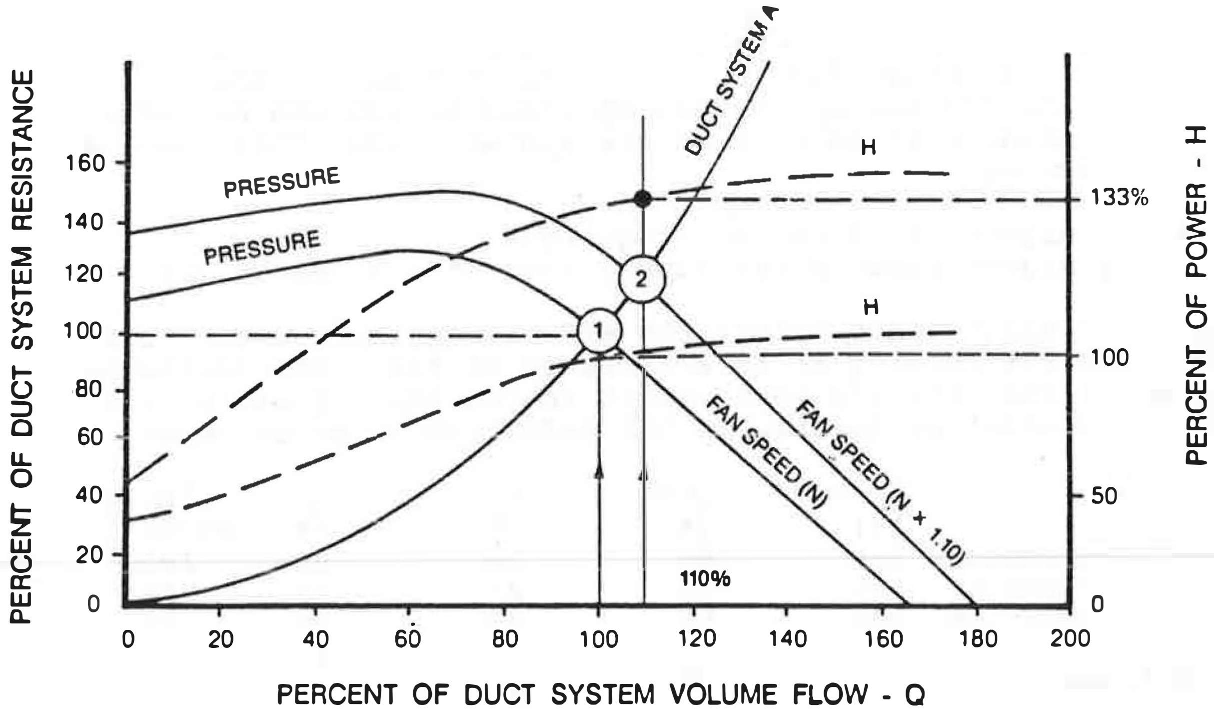


Fig. C.6 Effect of 10% Increase in Fan Speed.

System Effects on Fan Performance

A common technique of fan design and specification is that of comparing the system curve to fan curves and selecting on the basis of intersection. That is to say, the pressure loss versus volumetric air flow of a system can be determined independent of the fan and used to solve for variables using fan performance curves. Although A.M.C.A. has a methodology for modifying an external static curve to accommodate losses within a packaged air handler, it also assumes that fan characteristics are independent of installation geometry (see Fig. C.7).

In reality, however, the aerodynamics of entry and exit conditions significantly modify fan characteristics; see Figs. C.8 - C.11.

The velocity profile and turbulence generated by the local configuration impact flow within the fan. Also, the pressure drop of these external components depends on the velocity field. For example, a heat exchanger receiving a non-uniform air distribution immediately downstream of a centrifugal blower will have a higher pressure drop than a uniform face velocity test condition.

In many applications, it is not accurate or instructive to use a linear analysis. The immediate assembly must form the basis of analysis and good design will seek aerodynamic entry and exit conditions.

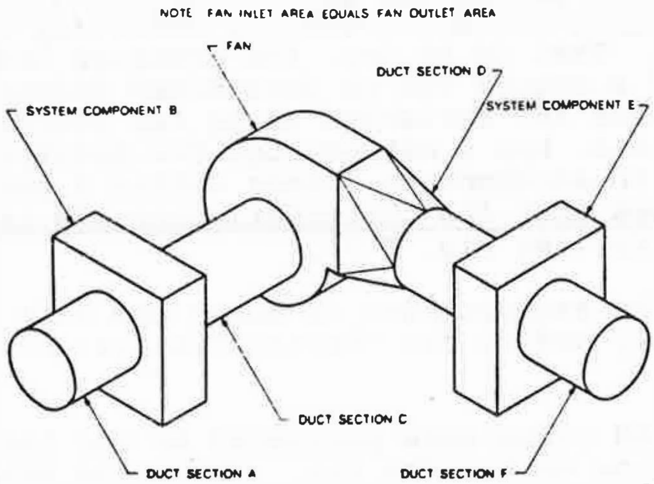


Fig. C.7 Typical Fan Duct System (Farquhar).

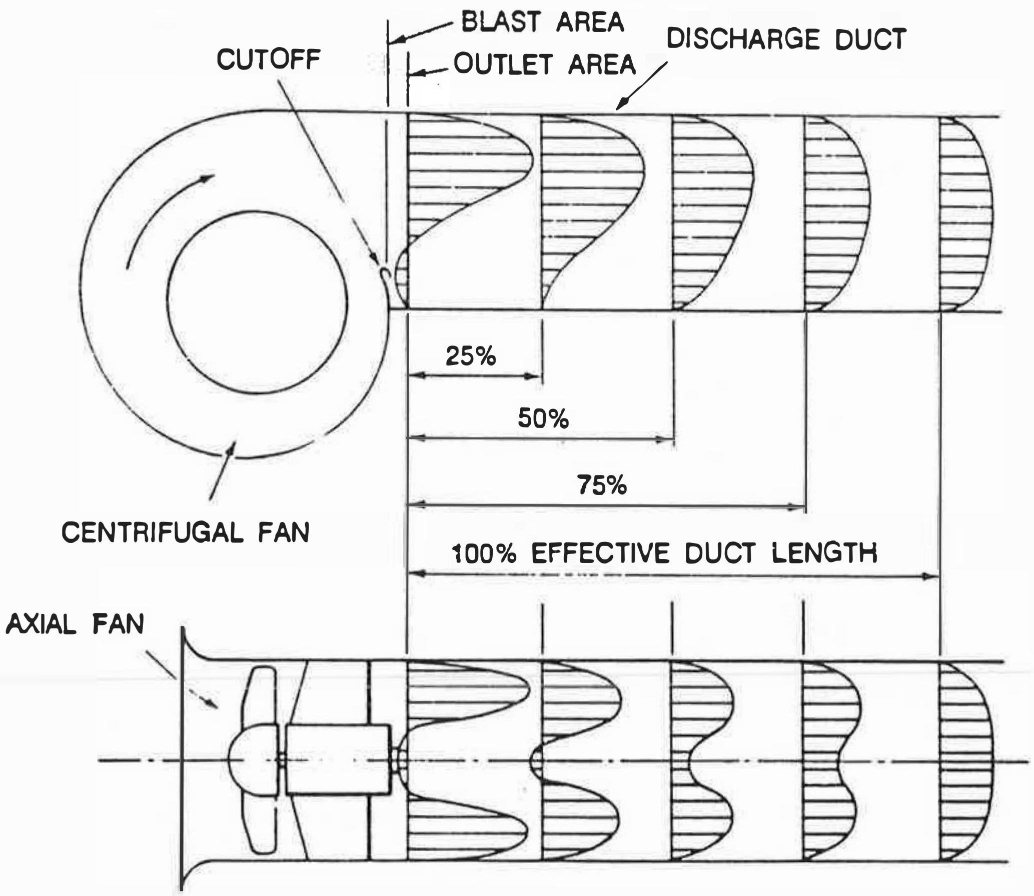


Fig. C.8 Fan Outlet Velocity Profiles (A.M.C.A.).

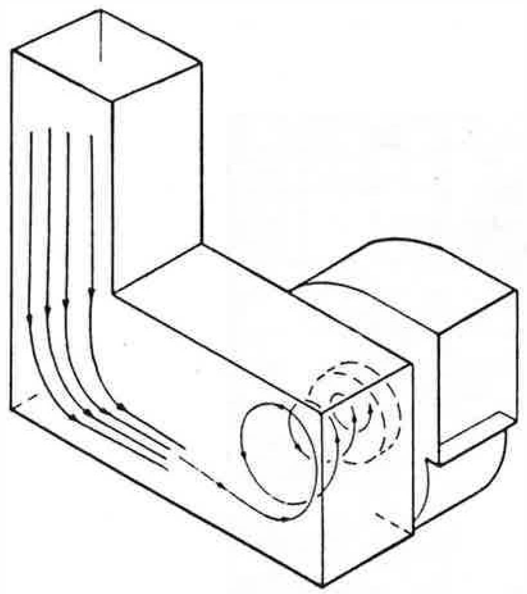


Fig. C.9 Example of a Forced Inlet Vortex (A.M.C.A.).

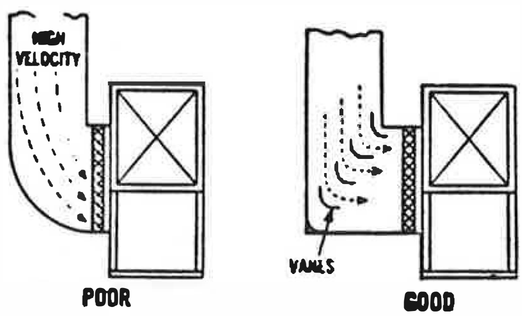


Fig. C.10 Uniform Inlet Distribution, Through Proper Use of Vanes Improves Fan Operation and Reduces Noise (Clifford).

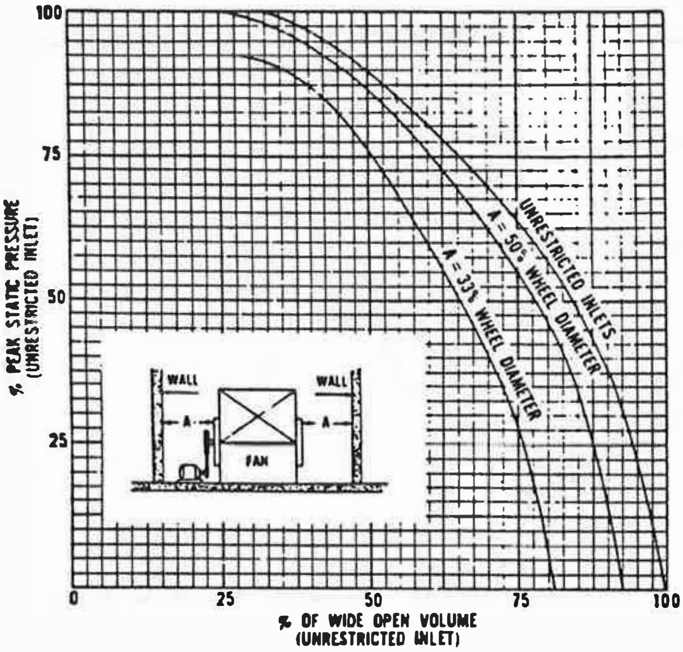


Fig. C.11 Space Restriction Reduces Fan Capacity as Indicated By These Curves From Tests on Double Inlet Fans (Clifford).

APPENDIX D: FAN AND FAN/MOTOR SET EFFICIENCIES FROM MANUFACTURERS' INFORMATION

APPENDIX D: FAN AND FAN/MOTOR SET EFFICIENCIES FROM MANUFACTURERS' INFORMATION

Notes for Tables D.1 and D.2

Methodology

The "Trade Commissioner" or "Consul" for each country that we anticipated may have companies that produce high efficiency fans or fan/motor combinations were contacted. Many of those contacted were very helpful, providing lists of potential manufacturers. From those lists, companies were contacted by fax, requesting information on their fans or fan/motor combinations with specific information relating to efficiency.

It was determined that if anyone required high efficiency fans that it would be the National Aeronautics and Space Administration for use in the space station now under development. They have limited electrical power available to them in space, yet need fans that move air effectively against a range of static pressures. They and their subcontractors were contacted.

Problems Encountered

Some Consuls or Trade Commissioners were of no help whatsoever. This may have been because there were no suitable products produced in their country or that no one at those companies understood English. Waiting for their response, or a response from their manufacturers took considerable time. Some of the European product literature that we received appeared to indicate that their products were very well engineered and more sophisticated than that available in North America, however, they could not provide the necessary information required to calculate the efficiency. Most could not provide data on airflow at given pressures (one half of the equation to calculate efficiency) but not the matching power input data. Nearly all of the available power input information was based upon motor input while the fan operated in free air. Those manufacturers that we spoke to indicated that no one had ever requested the information that we required, so no testing of this nature had been done. They seemed to know or believe that their fans were efficient because it was a design consideration from the beginning and they had used good engineering practice.

Considerable time was spent talking to very cooperative NASA officials and their sub-contractors to track down the sub-sub-contractor supplying the high efficiency fans, Hamilton Standard, a United Technologies Company. Once the supplier was found, it took some time to find the appropriate engineer to get further information. The engineer could not provide us with the information required directly; we had to work with the New Business Development Group. It took two months of hounding to get this group to obtain an provide the information we needed from the design/research engineer. (They were spending considerable time in Russia looking for new marketable technologies).

Results

Only two companies that produce fans that have efficiencies in the 60-70% range were found. One produced high efficiency centrifugal fans and the other bifurcated axial fans, in this efficiency range. In addition, Hamilton Standard has produced two high efficiency fans for NASA. These fans require the use of motors capable of 8000 to 13000 rpm. In addition, three sources of fan/motor combinations with efficiencies of 20-30% were found. This included centrifugal, axial, and aerofoil configurations. The efficiencies found in combinations may have been higher if more efficient motors had been used. Motor efficiencies were not provided in most cases, however, motor descriptions included with the fan literature received appears to indicate that shaded pole and other standard efficiency type motors were used. It is not apparent that any of the high efficiency fans found used plastic blades or housings. This was likely for two reasons: most European fans appeared to be custom made to purchasers' specific requirements and; many are used in locations where fire ratings would be a concern.

Recommendations

It appears that fan efficiencies of 60-70% can be achieved with current technology and when combined with motor efficiencies of approximately 70%, total efficiencies of 40-50% are possible. (High efficiency motors for small capacity fans may not be as readily available as those with ratings of 1/4 Hp or more). These efficiencies may be a suitable initial target range for Canadian fan standards.

One interesting and unique approach is Hamilton Standard's use of high rotational rates. Their fans have very flat curves over a wide range of flow rates and pressures. Their fan engineer advised that they must use high rotational rates to get the flows required from a fan of minimal size. This does increase noise levels somewhat, requiring some fan acoustical insulation, though the engineer did not believe that they were especially noisy. The engineer said that he believed that he could produce designs that would provide high efficiency over a wide range of flows and pressures, at lower turn rates. He appears to have a good grasp of fan principles and designs and is confident of his ability to produce whatever is required. Though we can not work directly with him and must deal with the company's "New Business Development Division", he is a potential resource person that could help to develop a line of high efficiency fans for the Canadian market. It is recommended that further discussions in this regard be held with Hamilton Standard.

Recommendations (Cont.)

Discussions with the Canadian furnace blower manufacturer, "Delhi" indicated that one of the problems that must be faced is that often fans are not installed in a manner that would optimize efficiency. In fact, installed efficiency is usually much less than would be the case if the fan and the application were designed with efficiency in mind. Therefore, any fan standard should require testing of the complete assembly in which the fan is installed.

Since there appears to be little activity anywhere in the world to develop high efficiency fans or fan/motor combinations for the residential market, there appears to be an excellent opportunity for Canada to take the lead in designing and producing a line of such products. Axial fans with capacities of 25, 50, 100, 150, and 200 L/s would be required for exhaust and other ventilation system uses and centrifugal fans for use as furnace blowers with capacities of 200 to 1000 L/s are required.

An independent design and engineering team could design these fans and license production to any Canadian company wishing to produce the product. Perhaps Hamilton Standard's engineering resources could help with this process. The products developed may also find a large world market.

DUCTED FAN EFFICIENCIES

MODEL	TYPE	MOTOR LOCATION	FAN INPUT W	AIR FLOW m3/h	AIR FLOW L/s	AIR PRESSURE Pa	FAN OUTPUT W	FAN EFFICIENCY	COMMENTS
MANUFACTURER: SPENCER									
CMV 125	CENTRIFUGAL	EXTERNAL	100	465	129.2	500	64.58	64.58%	
CMV 280	CENTRIFUGAL	EXTERNAL	1800	7900	2194	600	1316.67	73.15%	
MANUFACTURER: VICTORIA FAN									
244/4-8/45/3H	AXIAL	INTERNAL	2.24	180	50	23.75	1.19	53.01%	BIFURCATED, 900 RPM
244/4-8/45/3H	AXIAL	INTERNAL	2.61	90	25	30	0.75	28.74%	BIFURCATED, 2810 RPM
294/4-8/45/3H	AXIAL	INTERNAL	216.3	2160	600	240	144.00	66.57%	BIFURCATED, 1400 RPM
294/4-8/45/3H	AXIAL	INTERNAL	27.6	900	250	58.75	14.69	53.22%	BIFURCATED, 900 RPM
294/4-8/45/3H	AXIAL	INTERNAL	10.82	180	50	45	2.25	20.79%	BIFURCATED, 900 RPM
394/8/45/3H	AXIAL	INTERNAL	43.27	1800	500	45.75	22.88	52.87%	BIFURCATED, 900 RPM
394/8/45/3H	AXIAL	INTERNAL	134.28	1800	500	115	57.50	42.82%	BIFURCATED, 1400 RPM
594/10/45/3H	AXIAL	INTERNAL	328.24	2340	650	250	162.50	49.51%	BIFURCATED, 1400 RPM
MANUFACTURER: HAMILTON STANDARD									
MFF DST	MIXED FLOW	INTERNAL		900	250	1825	456.25	73.00%	AT 7000 RPM, 10 BLADES
IMV	AXIAL	INTERNAL		540	150	225	33.75	70.00%	AT 7765 RPM, 5-6 BLADES

DUCTED FAN/MOTOR EFFICIENCIES

MODEL	TYPE	MOTOR TYPE	MOTOR LOCATION	MOTOR VOLTAGE	MOTOR INPUT W	AIR FLOW m3/h	AIR FLOW L/s	AIR PRESSURE Pa	FAN/MOTOR OUTPUT W	FAN/ MOTOR EFFICIENCY	COMMENTS
MANUFACTURER: EBM*											
G2E 180-AA 03-01	CENTRIFUGAL	CAPACITOR	INTERNAL	220	300	535	148.6	550	81.74	27.25%	SINGLE INLET, SCROLL HSG, DIE CAST ALUM.
G2S 108-CD 02-01	CENTRIFUGAL	S. POLE	INTERNAL	220	57	150	41.67	50	2.08	3.65%	SINGLE INLET, SCROLL HSG & IMPELLER
D2E 097-BD 04	CENTRIFUGAL	CAPACITOR	INTERNAL	220	76	390	108.3	25	2.71	3.61%	DOUBLE INLET, SCROLL HSG & IMPELLER
D2E 133-DB 01	CENTRIFUGAL	CAPACITOR	INTERNAL	220	175	710	197.2	100	19.72	11.27%	DOUBLE INLET, SCROLL HSG & IMPELLER
G2E 140-AL 40-01	CENTRIFUGAL	CAPACITOR	INTERNAL	220	125	420	116.7	100	11.67	9.33%	SINGLE INLET, SCROLL HSG, DIE CAST ALUM.
G2E 160-AD 01-01	CENTRIFUGAL	CAPACITOR	INTERNAL	220	250	610	169.4	40	6.78	2.71%	SINGLE INLET, SCROLL HSG, DIE CAST ALUM.
MANUFACTURER : AIRFLOW											
52BTXL	CENTRIFUGAL	PERMANENT, SPLIT CAPAC., 2 POLE	EXTERNAL	220	115	325	90.28	210	18.96	16.49%	SINGLE INLET FAN
57 BXL	CENTRIFUGAL	PERMANENT, SPLIT CAPAC., 2 POLE	EXTERNAL	220	160	360	100	245	24.50	15.31%	SINGLE INLET FAN
76 E2WL/4	CENTRIFUGAL	PERMANENT, SPLIT CAPAC., 4 POLE	EXTERNAL	220	300	487	135.3	125	16.91	5.64%	DOUBLE INLET, MTR IN ONE INLET
83 F2WL	CENTRIFUGAL	PERMANENT, SPLIT CAPAC., 4 POLE	EXTERNAL	220	170	1270	352.8	58	20.46	12.04%	DOUBLE INLET, MTR IN ONE INLET
83 F2WXL	CENTRIFUGAL	PERMANENT, SPLIT CAPAC., 6 POLE	EXTERNAL	220	130	1150	319.4	63	20.13	15.48%	DOUBLE INLET, DOUBLE WIDTH
90 G2WL	CENTRIFUGAL	PERMANENT, SPLIT CAPAC., 4 POLE	EXTERNAL	220	700	525	145.8	200	29.17	4.17%	DOUBLE INLET, DOUBLE WIDTH
102 H2WL	CENTRIFUGAL	PERMANENT, SPLIT CAPAC., 6 POLE	EXTERNAL	220	600	900	250	125	31.25	5.21%	DOUBLE INLET, DOUBLE WIDTH
40 BTX	CENTRIFUGAL	2 POLE	EXTERNAL	220	100	75	20.83	75	1.56	1.56%	DUPLEX FANS, 1 MTR, TWO FANS
45 C2T	CENTRIFUGAL	4 POLE	EXTERNAL	220	62	175	48.61	38	1.85	2.98%	DUPLEX FANS, 1 MTR, TWO FANS
52 D2TX	CENTRIFUGAL	PERMANENT, SPLIT CAPAC., 4 POLE	EXTERNAL	220	130	310	86.11	50	4.31	3.31%	DUPLEX FANS, 1 MTR, TWO FANS
MANUFACTURER: ADVANCED DESIGN & MANUFACTURE											
INDUX ILF300	AXIAL	EXTERNAL ROTOR CAP. START	INTERNAL	220	175	150	41.67	405	16.875	9.64%	INLINE DUCT FAN
					223	750	208.3	235	48.96	21.95%	INLINE DUCT FAN
MANUFACTURER: WOODS FANS											
5J	AEROFOIL	INFORMATION NOT PROVIDED	INTERNAL	230	22	180	50	10	0.50	2.27%	ADJUSTABLE PITCH AEROFOIL
6J	AEROFOIL	INFORMATION NOT PROVIDED	INTERNAL	230	41.4	360	100	25	2.50	6.04%	ADJUSTABLE PITCH AEROFOIL
7J	AEROFOIL	INFORMATION NOT PROVIDED	INTERNAL	230	128.6	720	200	75	15.00	11.66%	ADJUSTABLE PITCH AEROFOIL
9J	AEROFOIL	INFORMATION NOT PROVIDED	INTERNAL	230	333.5	1620	450	75	33.75	10.12%	ADJUSTABLE PITCH AEROFOIL
12K	AEROFOIL	INFORMATION NOT PROVIDED	INTERNAL	230	575	1800	500	200	100.00	17.39%	ADJUSTABLE PITCH AEROFOIL
15J	AEROFOIL	INFORMATION NOT PROVIDED	INTERNAL	230	1357	5400	1500	200	300.00	22.11%	ADJUSTABLE PITCH AEROFOIL
12/33	AEROFOIL	INFORMATION NOT PROVIDED	INTERNAL	230	287.5	1584	440	25	11.00	3.83%	FIXED PITCH BIFURCATED
AXCENT 2, MX31	MIXED FLOW	INFORMATION NOT PROVIDED	EXT.BELT	400	508	2160	600	250	150.00	29.53%	INLINE MIXED FLOW
ILC 1	AXIAL	INFORMATION NOT PROVIDED	INTERNAL	230	46	136.8	38	50	1.90	4.13%	INLINE CENTRIFUGAL FAN
ILC 3	AXIAL	INFORMATION NOT PROVIDED	INTERNAL	230	94.3	352.8	98	100	9.80	10.39%	INLINE CENTRIFUGAL FAN
MANUFACTURER: WATER FURNACE											
AT	CENTRIFUGAL	ECM	INTERNAL	120	300	3420	950	82	77.90	25.97%	USED IN GROUND SOURCE H.P.'s
					400	5760	1600	167	267.20	66.80%	USED IN GROUND SOURCE H.P.'s

** These fans are all rated at their minimum acceptable static pressure as no other data was available. Efficiencies may be higher at higher statics.*

	Fan Type	Motor Input [W]	Air Flow [L/s]	Static Pressure [Pa]	ε_{mf} %
<u>Exhaust Fans</u>					
Broan 600* Builders Series	Paddle	?	28	25	very low?
Reversomatic EB55 2200 rpm	F/C	134	25	25	0.5
Broan Losone 360 1200 rpm	F/C	84	45	25	1.4
Nutone 695C* Builders Series	?	144	33	25	0.6
Nutone 8632C	F/C	102	50	25	1.2
Nutone 671C	F/C	60	42	25	1.8
Nutone 822 Thru-wall	7" T/A	98	100	8	0.8
<u>Eastern Air Devices</u>					
EAD V-Line 200 19,000 rpm	2" V/A	40	25	25	1.6
EAD V-Line 475 3700 rpm	5" V/A	40	47	100	11.8
EAD T-Line 600 1725 rpm	7" T/A	25	94	55	20.7
EAD B20 H25 9000 rpm	F/C	54	22	375	15.3
EAD B37 H25D	R/C	-	25	625	-
EAD BM 70B34 1650 rpm	M/F	70	85	75	9.1

* **Assembled on-site**

Table D.3 Various Fan/Motor Set Efficiencies Derived From Product Literature.

	Fan Type	Motor Input [W]	Air Flow [L/s]	Static Pressure [Pa]	ε_{mf} %
Kanalflakt					
ACK 5M 3100 rpm	5" B/C	44	49	88	9.7
ACK 12M 1610 rpm	12" B/C	152	218	175	25.5
DCK 5M/24V 2850 rpm	5" B/C	27	45	118	19.6
EBM					
G2E140AL40	F/C	125 W	106	150	12.7
Allen Associates					
Torin Blower Universal PSC motor	F/C	105 W	300	125	34

F/C = forward-curved centrifugal
B/C = backward-curved centrifugal in-line
R/C = radial centrifugal
M/F = mixed-flow
V/A = vane axial
T/A = tube axial

Table D.3 Various Fan/Motor Set Efficiencies Derived From Product Literature (Cont.).

APPENDIX E: SOME COSTING DATA

APPENDIX E: SOME COSTING DATA

The following prices were obtained from manufacturers price lists and interviews. Note that OEM prices may be 1/3 the noted costs and trade prices, 2/3. Indications are that motors used most commonly in the industry may be sold as low as 1/5 the list price. The listed motors are 1550 rpm to 1800 rpm motors.

HP	ε [%]	Type	List Price [$]
1/250	8	Shaded Pole	45
1/120	13	Shaded Pole	48
1/60	17	Shaded Pole	52
1/30	18	Shaded Pole	58
1/6	21	Shaded Pole	120
1/6	35	PSC 3-Speed	142
1/6	49	PSC 3-Speed (230V)	145
1/6	66	High-Efficiency (230V)	120
1/6	73	ECM	140
1/4	30	Split Phase	140
1/4	44	PSC	155
1/4	48	High-Efficiency	?
1/4	72	ECM	385
1/3	35	Split Phase	140
1/3	44	PSC	145
1/3	54	High-Efficiency	?
1/3	79	ECM	435
3	90	High-Efficiency	525

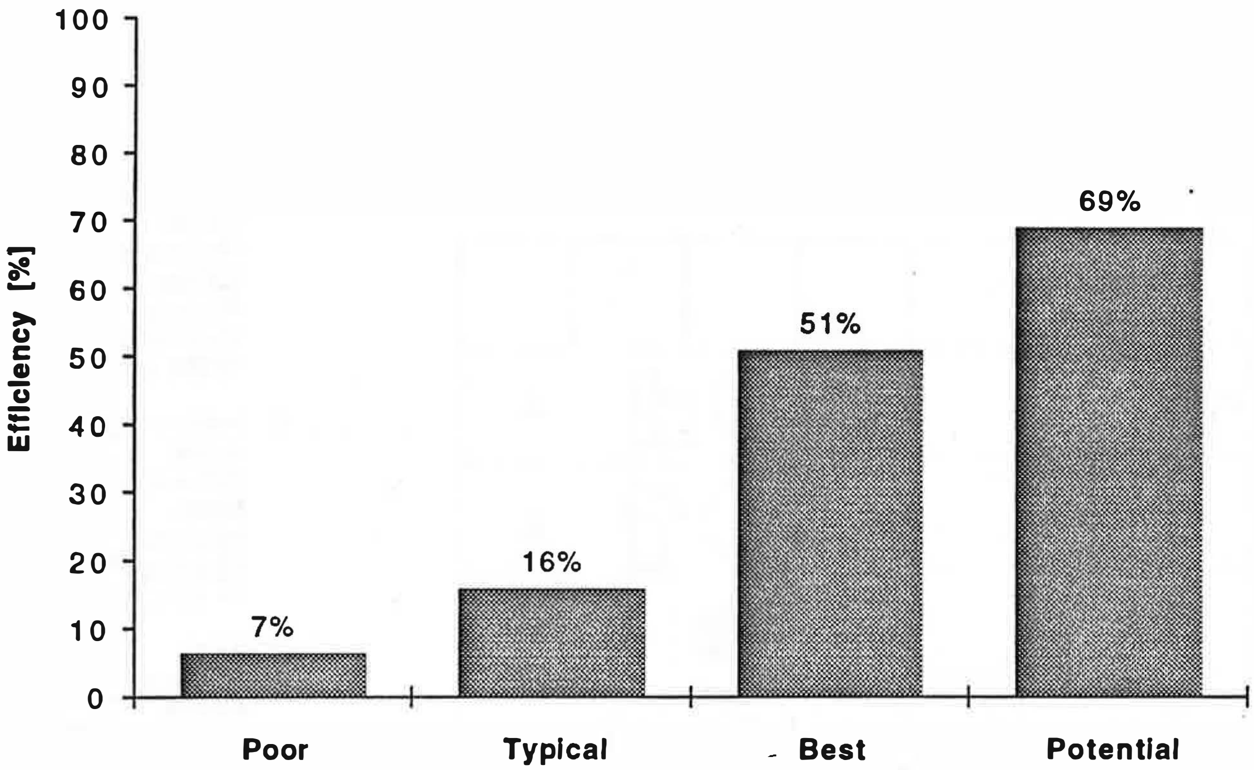
Table E.1 Motors

Note: For the purpose of this table, efficiency is defined as shaft output divided by full load Volt-amps. Note that tested curent values may be lower than those quoted in product literature. The following is an example of a 1/4 Hp [250 W], high efficiency AC motor tested at Ontario Hydro (0.8 power factor, 115 V):

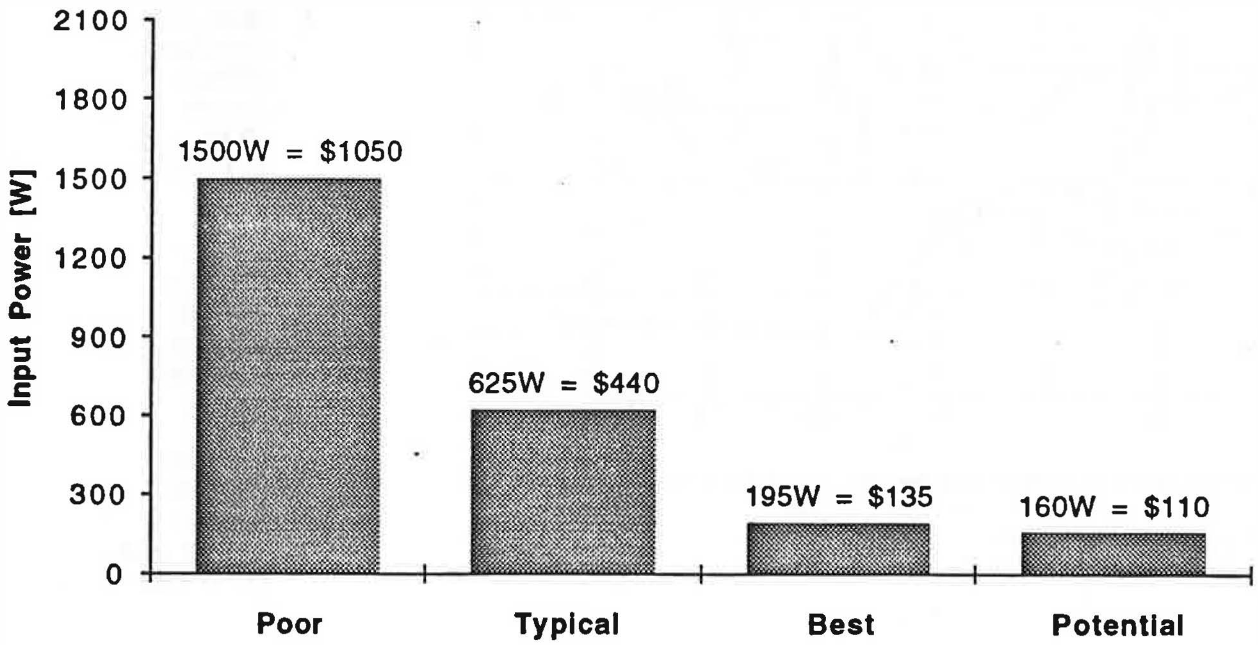
	Amps	ε [%]
Product Literature	3.40	60
Tested Values	2.75	74

	Trade [$]	List [$]
Bathroom Fans		
Low Cost Builders Series	-	12
Conventional Higher Quality	-	35
Central Exhauster		
Backward Curved Inline	110	-
Backward Curved w/ PSC Motor	110	240
Backward Curved w/ ECM Motor	250	-
Furnace Fan		
Conventional	-	250
Backward Curved w/ High-Eff. Motor	-	500

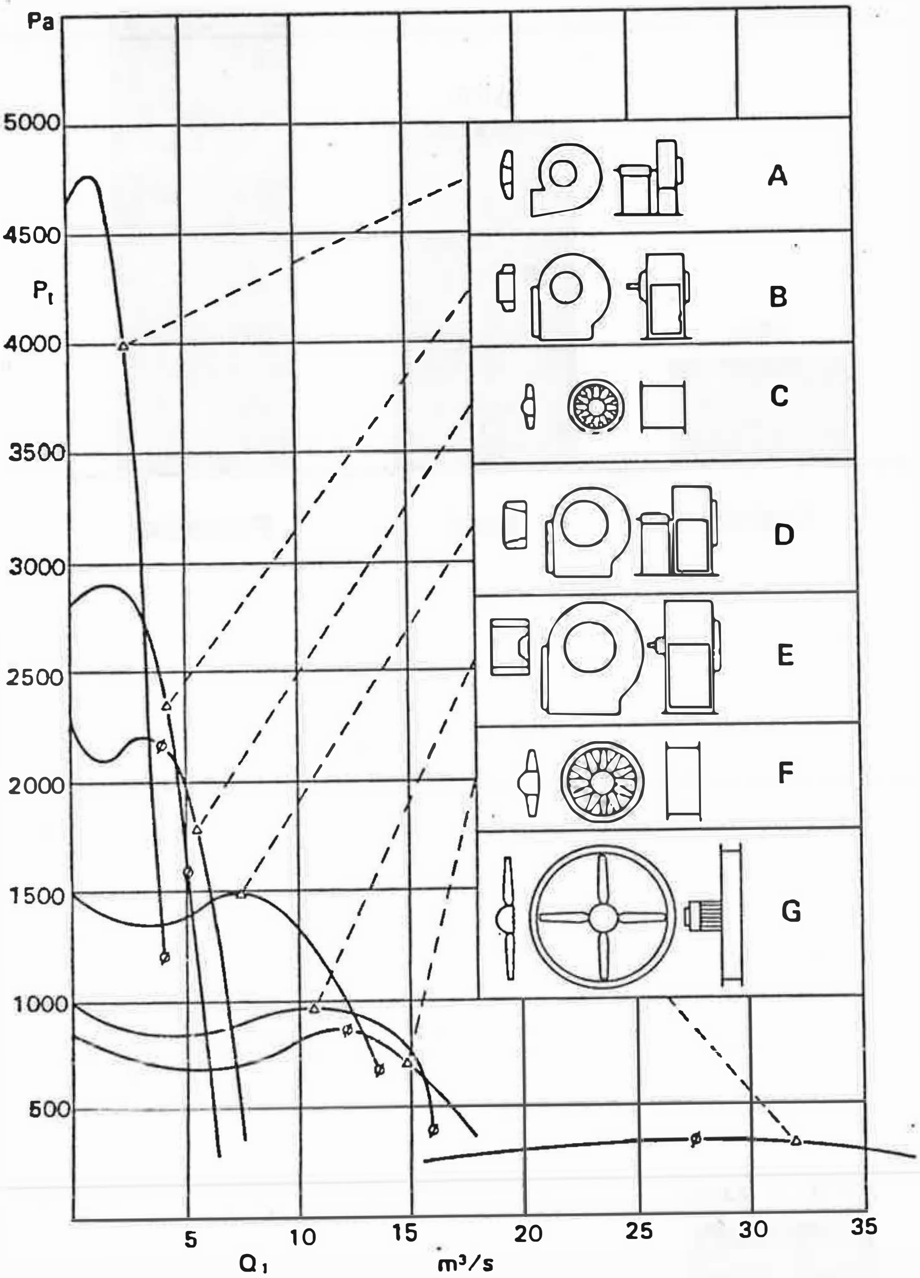
Table E.2 Fan/Motor Combinations



100
90
80
70
60
50
40
30
20
10
0
Efficiency [%]
7%
16%
51%
69%
Poor
Typical
Best
Potential



2100
1800
1500
1200
900
600
300
0
Input Power [W]
1500W = $1050
625W = $440
195W = $135
160W = $110
Poor
Typical
Best
Potential



Each fan, operating at top speed and best efficiency point Δ is chosen for an output $Q \times P_t = 10$ kW.

Peak input power is taken at Ø

Drawings are to a uniform scale of 1:100

A Backward-curved
Half-width
630mm
42 rev/s
13·5 kW at Δ
17 kW at Ø

B Backward-curved
Full-width
630mm
36 rev/s
12 kW at Δ
14 kW at Ø

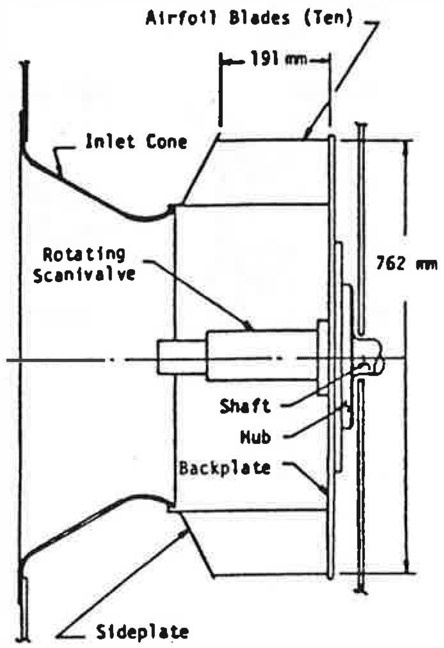
C Axial
50% hub
630mm
48 rev/s
13·5 kW at Δ
15 kW at Ø

D Forward-curved centrifugal
700mm
18 rev/s
15 kW at Δ
30 kW at Ø

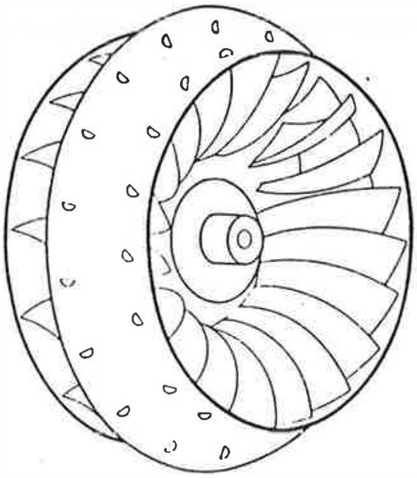
E Multi-vane centrifugal
850mm
9 rev/s
15 kW at Δ
30 kW at Ø

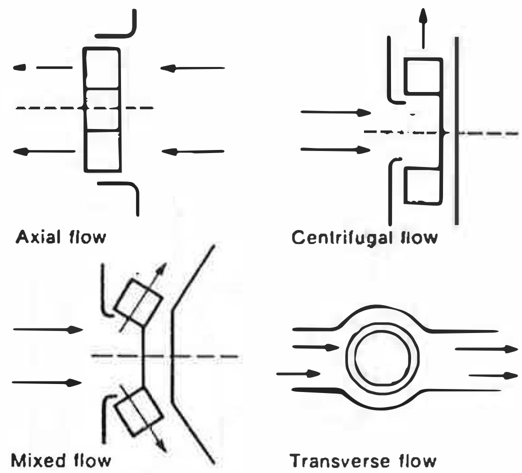
F Axial
35% hub
1000mm
24 rev/s
13 kW at Δ
15 kW at Ø

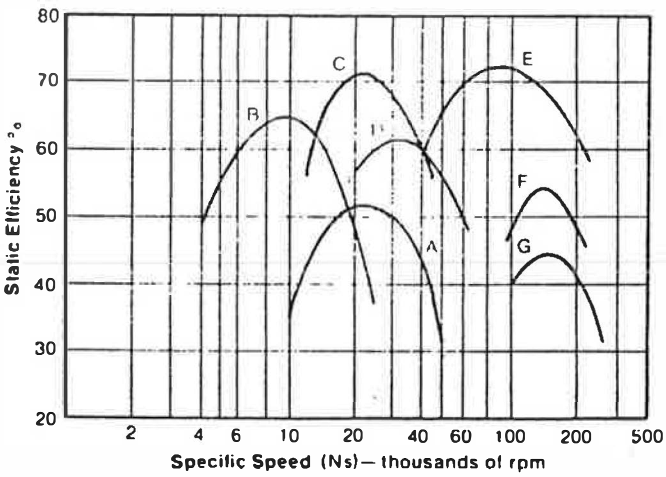
G Axial
25% hub
2000mm
12 rev/s
12·5 kW at Δ
14 kW at Ø



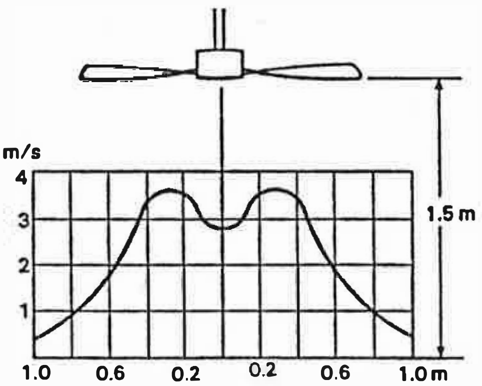
Airfoil Blades (Ten)
191 mm
Inlet Cone
Rotating
Scanivalve
762 mm
Shaft
Hub
Backplate
Sideplate







Type A Forward-Curved Centrifugal
B Backward-Curved Centrifugal (Narrow)
C Backward-Curved Centrifugal (Wide)
D Mixed Flow
E Vane Axial
F Tube Axial
G Propeller Fan



CEILING FAN
1400mm diameter
3·5 rev./s (210 rev/min)
120W input

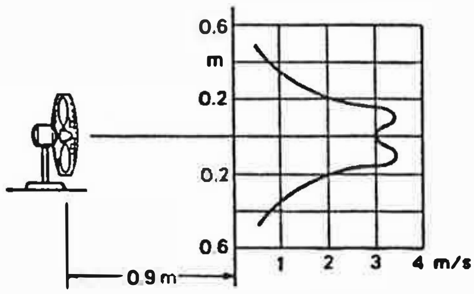
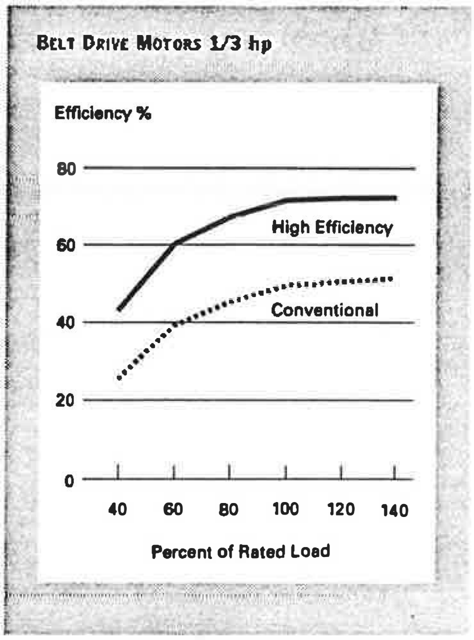


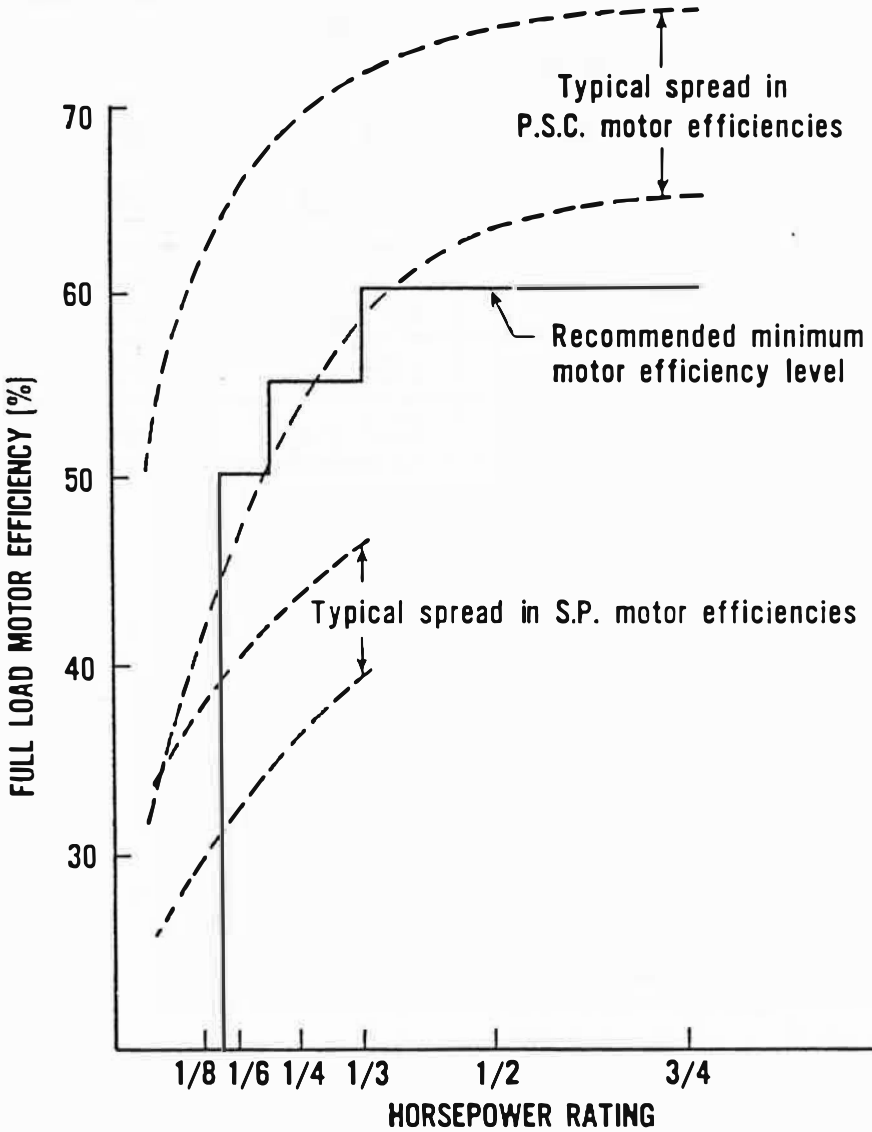
TABLE FAN
300mm diameter
23 rev/s (1380 rev/min)
60W input



Belt Drive Motors 1/3 hp
Efficiency %
80
60
40
20
0
High Efficiency
Conventional
40
60
80
100
120
140
Percent of Rated Load

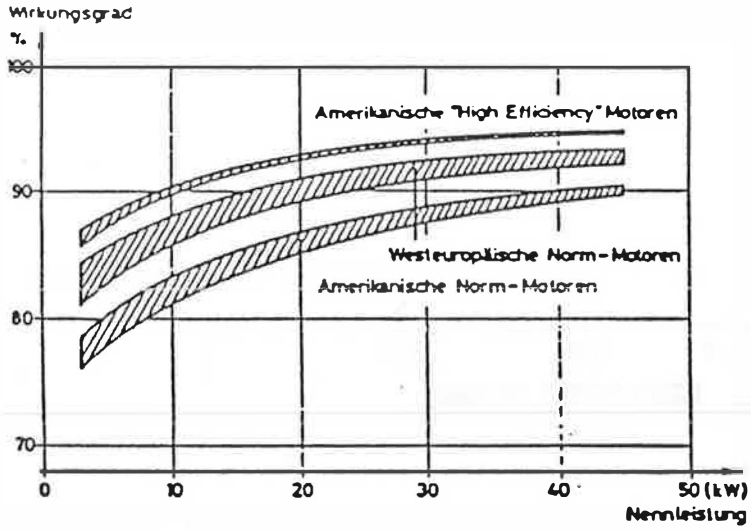
Type of Motor	Shaded Pole	Split Phase	Capacitor Start	Permanent Split-Capacitor
Description	Single Phase—starting torque provided by a permanently short-circuited auxiliary winding.	Single Phase with auxiliary starting winding connected in parallel with main winding. A starting relay is needed.	A modification of the split phase. The auxiliary starting winding is connected in series with an external capacitor.	A modification of the split phase. The main and auxiliary windings, in series with a continuous duty capacitor, are in the circuit at all times.
H.P. Range	1/1000 to 1/4	1/20 to 1	1/20 to 3	1/100 to 1
Rated Speed (60 Hz)	1050, 1550, 3100	860, 1140, 1725, 3450	860, 1140, 1725, 3450	1075, 1625, 3250
% Efficiency	10 to 40	35 to 60	35 to 60	30 to 60
Power Factor	.50 to .70	.55 to .70	.55 to .70	.85 to .95
Starting Torque (% of full load)	20 to 80	90 to 200	160 to 350	30 to 100
Application	Direct drive, low-power fans requiring long life without maintenance.	Suitable for frequent starting of fans and blowers—in direct and belt drive units.	All purpose motor for high starting torque, low starting current—in direct and belt drive units.	For direct drive units and multi-speed operation.
Advantages	a. Inexpensive b. Multi-speed operation c. Compact	a. Good starting torque b. Medium efficiency	a. Very high starting torque	a. Very high efficiency and power factor b. Steep speed-torque curve c. Multi-speed operation d. High inherent impedance protection e. Reversing operation f. Quietest of all small induction motors
Disadvantages	a. Low efficiency b. Low starting torque	a. Not applicable for special characteristics such as high starting torques, high efficiency and power factor, constant or adjustable speed	a. More expensive b. Non-adjustable speed	a. Low starting torque b. Speed varies under load

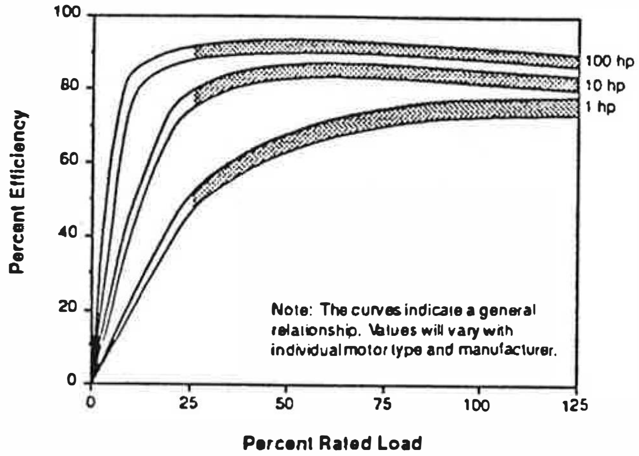
typical good-quality carbon steel	10.-11.
low-grade silicon steel	7.9
medium-grade silicon steel	5.5
modern nonoriented silicon steel	2.-4.
grain-oriented silicon steel	1.2
best laser-scribed production steel	1.1
best doubly-oriented lab silicon steel	0.4
amorphous pre-production FeNiBSi	0.3
best lab FeNiBSi	0.03-0.1

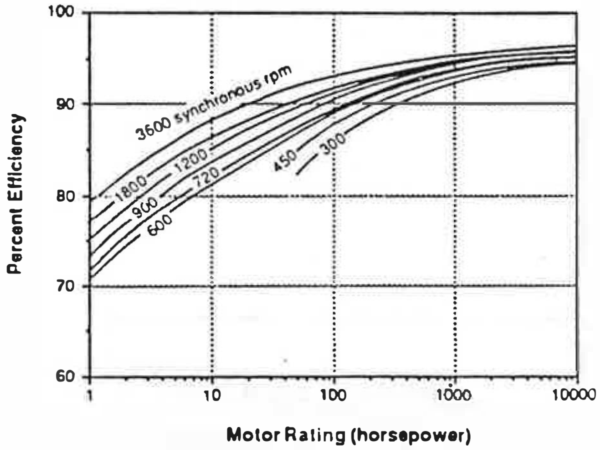


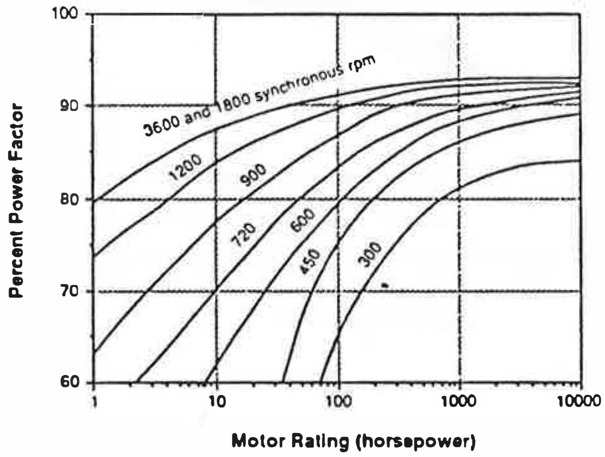
70
60
50
40
30
FULL LOAD MOTOR EFFICIENCY (%)
Typical spread in
P.S.C. motor efficiencies
Recommended minimum
motor efficiency level
Typical spread in S.P. motor efficiencies
1/8
1/6
1/4
1/3
1/2
3/4
1
HORSEPOWER RATING

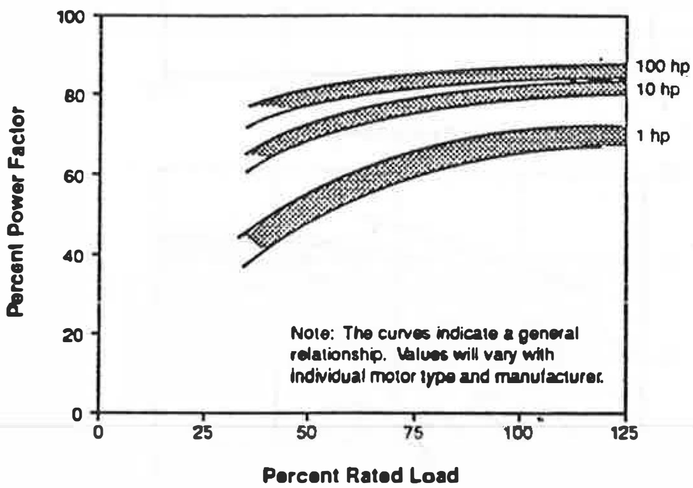
Motor*	Rated Power (watts)	Rated Speed	Efficiency at Rated Output
1/3 hp SE motor tested	250	1725 rpm	50.8%
1/3 hp HE motor tested	250	1725 rpm	74.5%
1/3 hp HE motor 2	250	1725 rpm	73.7%
1/3 hp HE motor 3	250	1725 rpm	70.2%
1/4 hp SE motor tested	187	1725 rpm	48.2%
1/4 hp HE motor tested	187	1725 rpm	75.4%




100
80
60
40
20
0
0
25
50
75
100
125
Percent Efficiency
Percent Rated Load
100 hp
10 hp
1 hp
Note: The curves indicate a general relationship. Values will vary with individual motor type and manufacturer.


100
90
80
70
60
1
10
100
1000
10000
Percent Efficiency
Motor Rating (horsepower)
3600 synchronous rpm
1800
1200
900
720
600
450
300

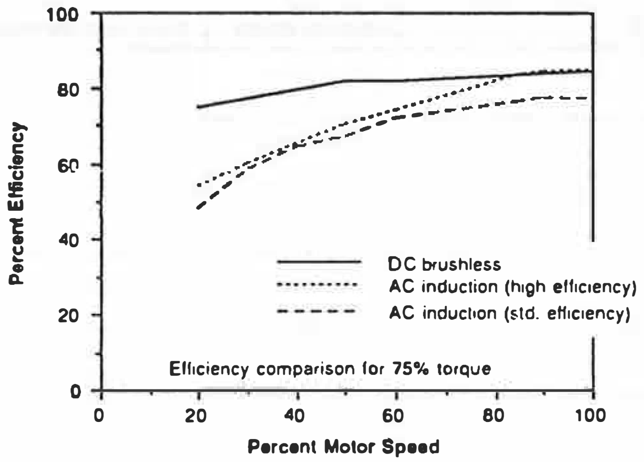

100
90
80
70
60
1
10
100
1000
10000
Percent Power Factor
Motor Rating (horsepower)
3600 and 1800 synchronous rpm
1200
900
720
600
450
300



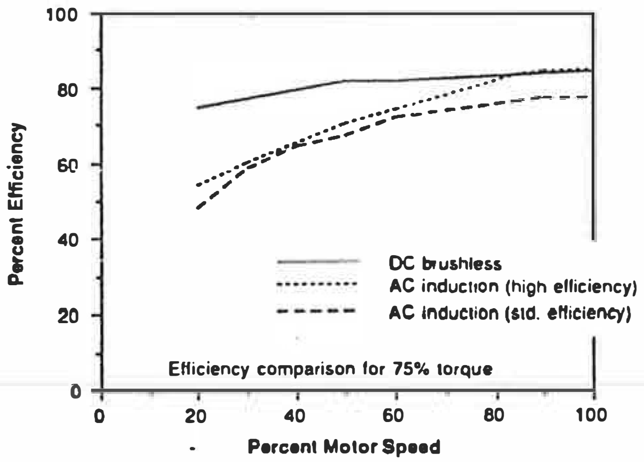
100
80
60
40
20
0
Percent Power Factor
100 hp
10 hp
1 hp
Note: The curves indicate a general relationship. Values will vary with individual motor type and manufacturer.
0
25
50
75
100
125
Percent Rated Load

	Technology		Applicability (R = Retrofit; N = New)	Cost	Comments
Motors	Multispeed (incl. PAM[1]) Motors		Fractional-500 hp PAM: fractional-2,000+ hp R,N	1.5 to 2 times the price of single-speed motors	Larger and less efficient than 1-speed motors. PAM more promising than multi-winding. Limited number of available speeds.
	Direct-Current Motors		Fractional-10,000 hp N	Higher than AC induction motors	Easy speed control. More maintenance required.
Shaft-Applied Drives (on Motor Output)	Mechanical	Variable-Ratio Belts	5–125 hp N	\$350–\$50[2]/hp (for 5–125 hp)	High efficiency at part load. 3:1 speed range limitation. Requires good maintenance for long life.
		Friction Dry Disks	Up to 5 hp N	\$500–\$300/hp	10:1 speed range. Maintenance required.
	Eddy-Current Drive		Fractional-2,000+ hp N	\$900–\$63/hp (for 1 to 150 hp)	Reliable in clean areas. Relatively long life. Low efficiency below 50% speed.
	Hydraulic Drive		5–10,000 hp N	Large variation	5:1 speed range. Low efficiency below 50% speed.
Wiring-Applied Drives (on Motor Input)	Electronic Adjustable Speed Drives	Voltage-Source Inverter	Fractional-1,000 hp R,N	\$1500–\$80/hp (for 1 to 300 hp)	Multi-motor capability. Can generally use existing motor. PWM[3] appears most promising.
		Current-Source Inverter	100–100,000 hp R,N	\$200–\$30/hp (for 100 to 20,000 hp)	Larger and heavier than VSI. Industrial applications, including large synchronous motors.
		Others	Fractional-100,000 R,N	Large variation	Includes cycloconverters, wound rotor, and variable voltage. Generally for special industrial applications.

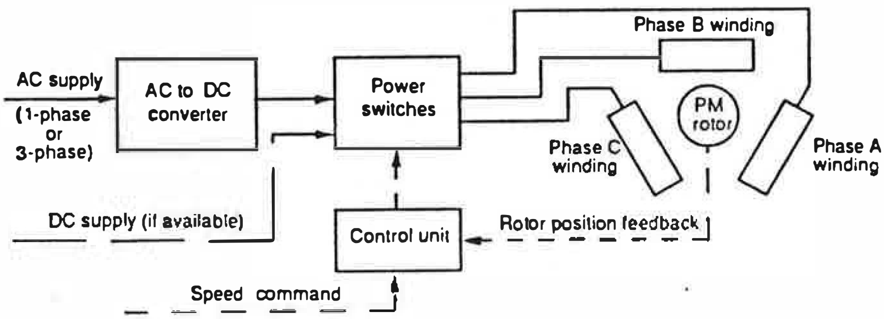
[1]PAM means Pole Amplitude Modulated. [2]The prices are listed from high to low to correspond with the power rating, which is listed from low to high. Thus, the lower the power rating, the higher the cost per horsepower. [3]PWM means Pulse Width Modulation.



100
80
60
40
20
0
Percent Efficiency
DC brushless
AC induction (high efficiency)
AC induction (std. efficiency)
Efficiency comparison for 75% torque
0
20
40
60
80
100
Percent Motor Speed



100
80
60
40
20
0
Percent Efficiency
DC brushless
AC induction (high efficiency)
AC induction (std. efficiency)
Efficiency comparison for 75% torque
0
20
40
60
80
100
Percent Motor Speed



PM Motors in Residential Appliances

An ever-increasing number of residential appliances use PM motors. A particularly innovative example is the Carrier Weathermaker SXi gas-fired, forced-air furnace (also sold under the Bryant, Day and Night, and Payne brand names). Like many top-of-the-line furnaces, it uses a condensing heat exchanger for high thermal efficiency, and an induced-draft exhaust blower to vent the flue gases. Unlike most others, this furnace is also electrically efficient, due to the use of two electronically commutated motors: one for the main ventilation fan, the other for the induced-draft blower.

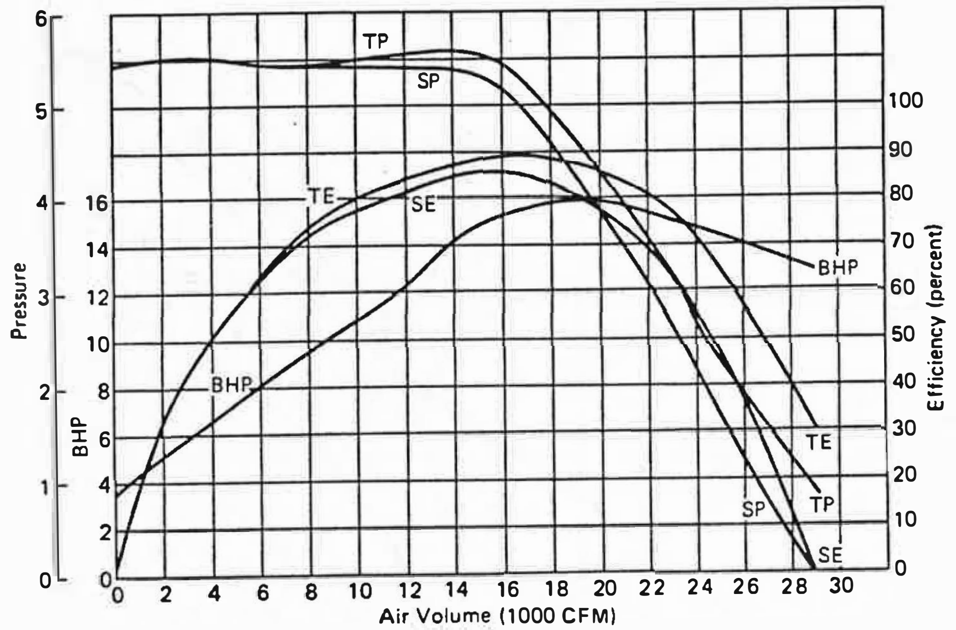
The burner operates in two stages, allowing the furnace to operate at low output for most of the required heating hours. The corresponding low speed of the main fan results in a power consumption of less than 100 W, compared to 600–1,000 W in a typical furnace. The low-speed capabilities, combined with sophisticated controls, also bring increased comfort and reduced noise. The installed cost of the furnace is about $2,500, roughly $300 to $700 more than other condensing furnaces (Nisson 1988).

Efficiency	Blower Configuration
80%	Backward Curved Wheel (1650 mm dia.)
70%	Backward Curved Wheel (300 mm dia.), or Forward Curved Wheel (900 mm dia.)
60%	Forward Curved Wheel (300 mm dia.)
50%	Forward Curved Wheel (250 mm dia., direct drive)
40%	Forward Curved Wheel (225 mm dia., tight housing), or Forward Curved Wheel (225 mm dia., standard housing, with belt drive losses)

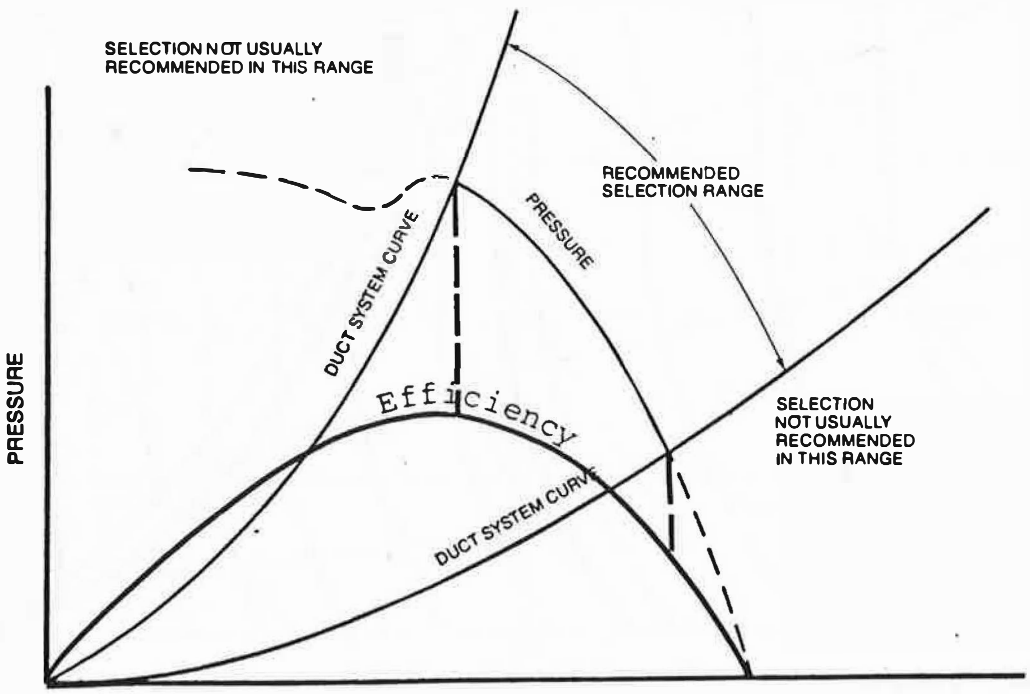
Table 1 - Peak Blower Efficiencies Within Manufacturer's Recommended Range					
Manufacturer	Wheel Length (in.) *	Standard Blower Housings		Tight Blower Housings	
		belt drive	direct drive	belt drive	direct drive
Lau	9.5	55%	46%	44.6%	N/A
Lau	8	53.8%	50%	42.8%	N/A
Lau	7.12	54.7%	52%	48%	N/A
Air Vector	9.5	N/A	53%	N/A	44%
Air Vector	8	N/A	53%	N/A	42%
Air Vector	7.12	N/A	57%	N/A	43%

Table 3 - Alternative Blower Designs With Efficiency Improvements			
Type of Blower	Manufacturer	Description	Peak Efficiency
plastic, backward inclined	M.K. Plastics (Montreal)	wheel dia.= 10.5 in. wheel length = 8-1/16"	65%
metal - forward curved (Fergas wheel)	Beckett Air (Ohio)	wheel diameters only up to 4.75"	claims to improve efficiency from 57% to 62%

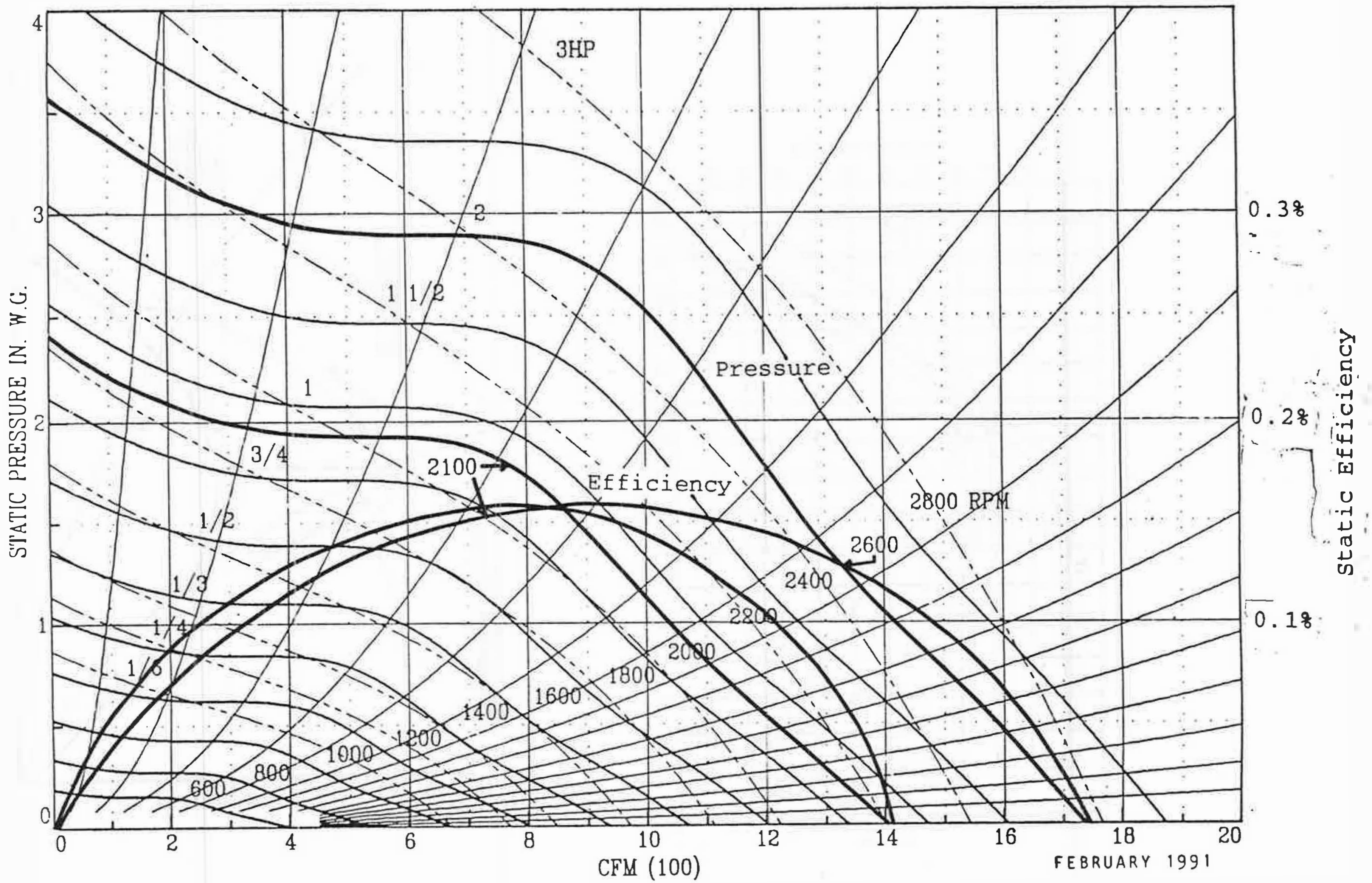
Design Parameter	Impact on Efficiency	Comments
Blade Design - outlet blade angle - number of blades - chord of blade (or radial depth)	- backward curved blades could increase efficiency by up to 20% - doubling the length of the blade could increase the efficiency by 20%	- in general, blowers with backward curved blades provide the flow rates at higher static pressures (however, Westinghouse developed a blower which may be suitable) - more blades increase skin friction losses but decrease eddy current losses - for similar flow, both power and speed decrease as blade depth is increased
Bearings	- 15-34 watts can be saved by using ball bearings instead of sleeve (increase in efficiency of 4-8%)	- no increase in sound level measured with ball bearings
Casing Design - size of casing - inlet vanes - outlet diffuser guide vanes - clearance between inlet nozzle and impeller eye	- a wheel will have an optimum casing size, deviation from which could degrade efficiency by up to 16% - efficiency not greatly effected by inlet vanes - guide vanes will increase efficiency by reducing shock and eddy losses - with a backward curved blade, the efficiency can be increased by 10% by tightening the clearance from 10 to 1 mm.	- positive pre-rotation provided by inlet vanes will change static head and power in proportion - if flow varies from design conditions, then vanes may increase losses (mainly used in high pressure blowers)
Cut-Off Design - clearance to impeller - location of cut-off - slope of cut-off	- deviation from the optimum cut-off clearance can reduce efficiency by up to 7% - efficiency can drop off by 4% with 25% of wheel diameter exposed	- sloping the cut-off reduces noise and therefore should improve efficiency
Type of Drive -direct drive vs belt drive	- for the same impeller wheel and housing, direct drive can be up to 9% less efficient	- direct drive blowers have lower costs and fewer installation problems (eg. poor tensioning of belts, or poor quality of pulleys) - efficiency of direct drive blowers could increase if motor was somewhat removed from blower inlet
Wheel, or Impeller Design - length/diameter ratio - material used	- the ratio can effect the efficiency by up to 6%	- there may be an optimum length/diameter ratio for each wheel diameter - plastic wheels are lighter and therefore put less loading on motor bearings (for direct drive)
Material Roughness	- at similar flow conditions, pump efficiency increases by 3% when a surface roughness of 0.005 inches is polished	- at low fan Reynolds numbers, the fan efficiency can drop by up to 10%, therefore coatings could help to minimize the relative roughness and minimize the change in efficiency - may present potential for plastic coatings



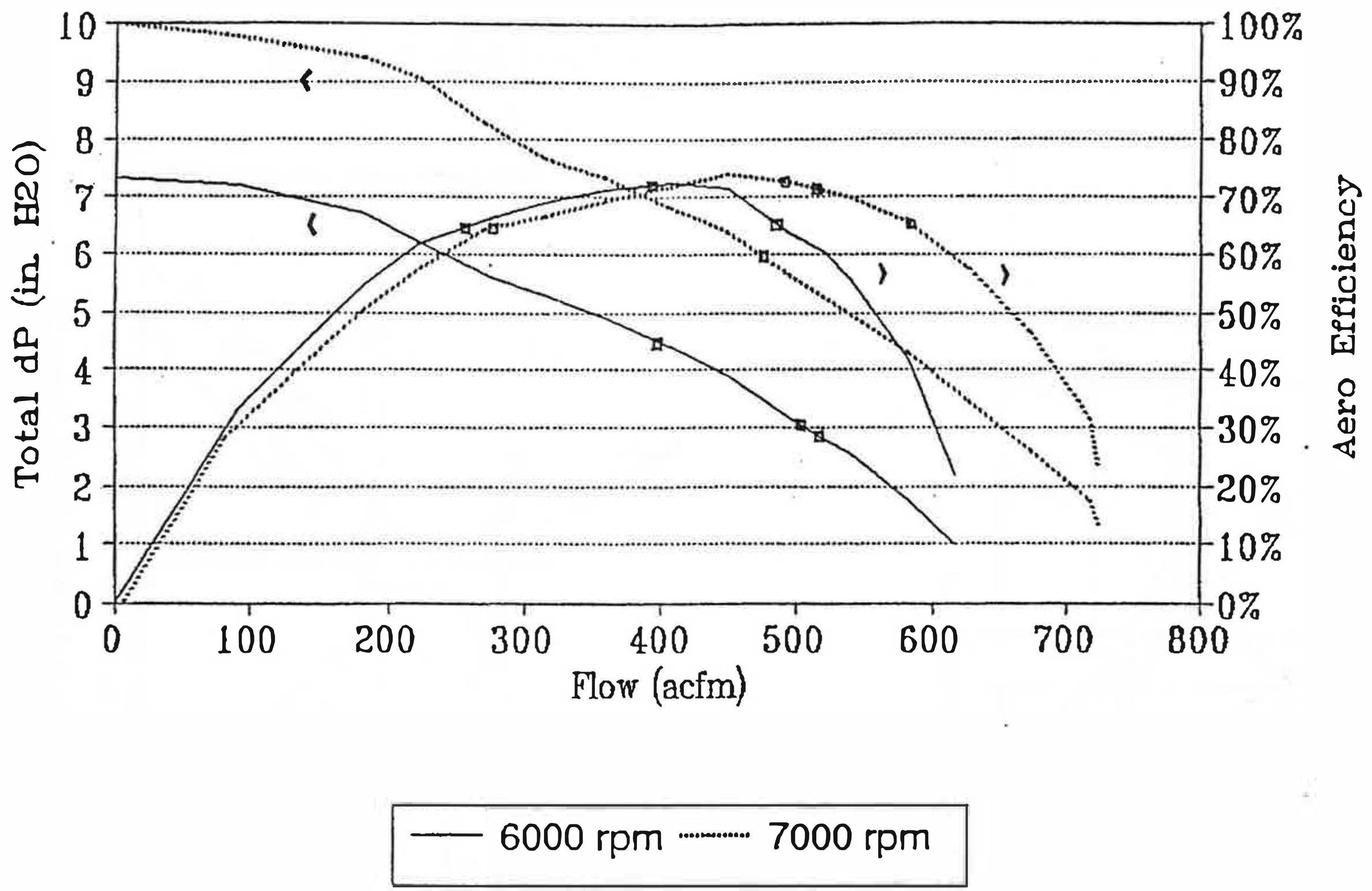
Pressure
BHP
Efficiency (percent)
Air Volume (1000 CFM)
TP
SP
TE
SE
BHP
0
1
2
3
4
5
6
0
2
4
6
8
10
12
14
16
0
10
20
30
40
50
60
70
80
90
100
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30



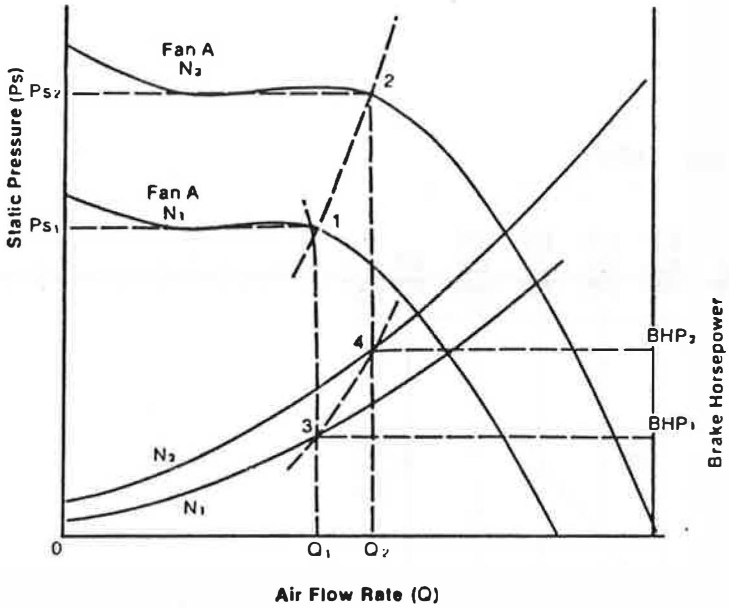
SELECTION NOT USUALLY RECOMMENDED IN THIS RANGE
RECOMMENDED SELECTION RANGE
PRESSURE
DUCT SYSTEM CURVE
Efficiency
DUCT SYSTEM CURVE
SELECTION NOT USUALLY RECOMMENDED IN THIS RANGE
PRESSURE



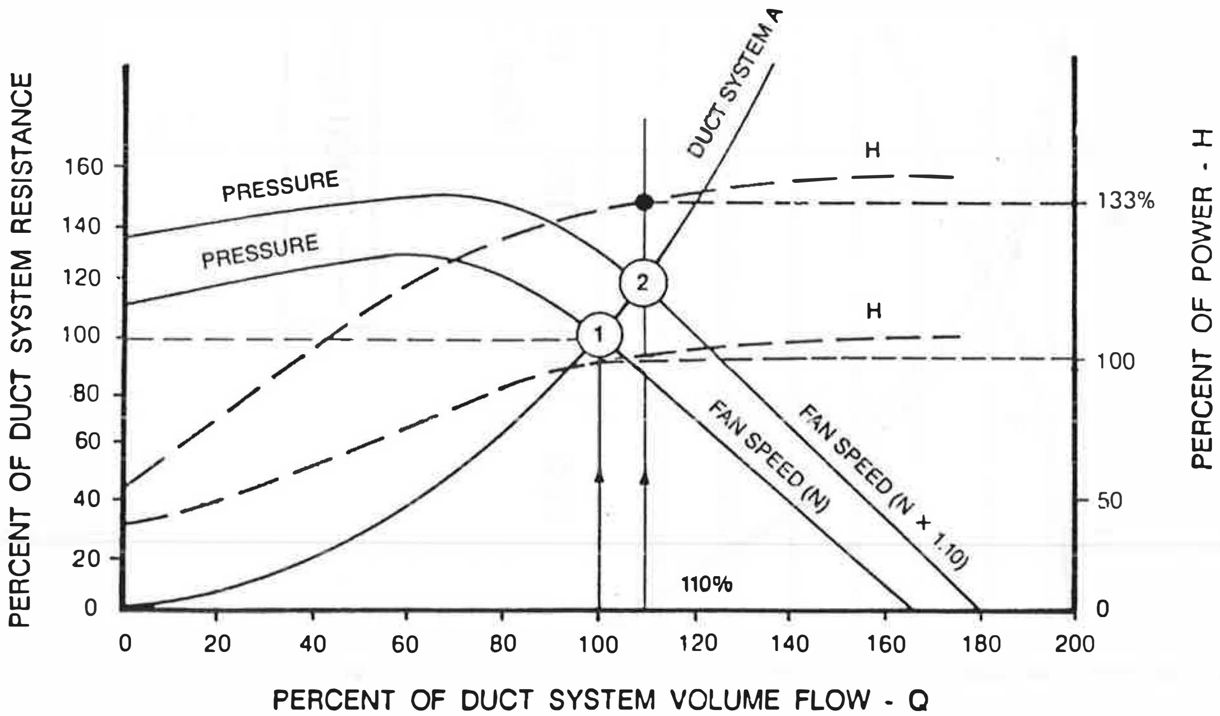
FEBRUARY 1991



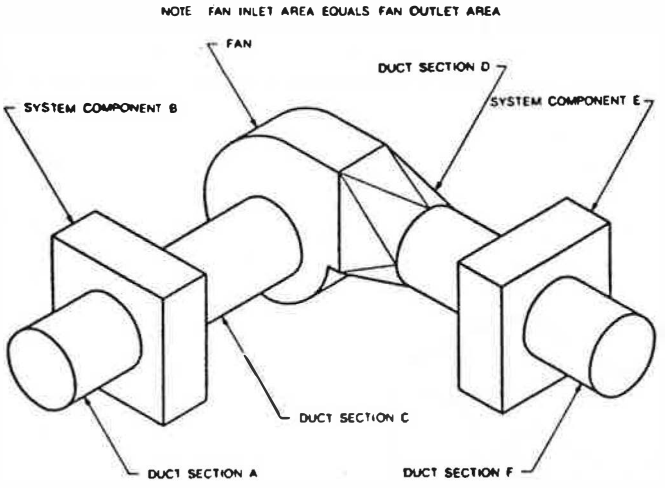
Total dP (in. H2O)
10
9
8
7
6
5
4
3
2
1
0
0
100
200
300
400
500
600
700
800
Flow (acfm)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Aero Efficiency
6000 rpm
7000 rpm

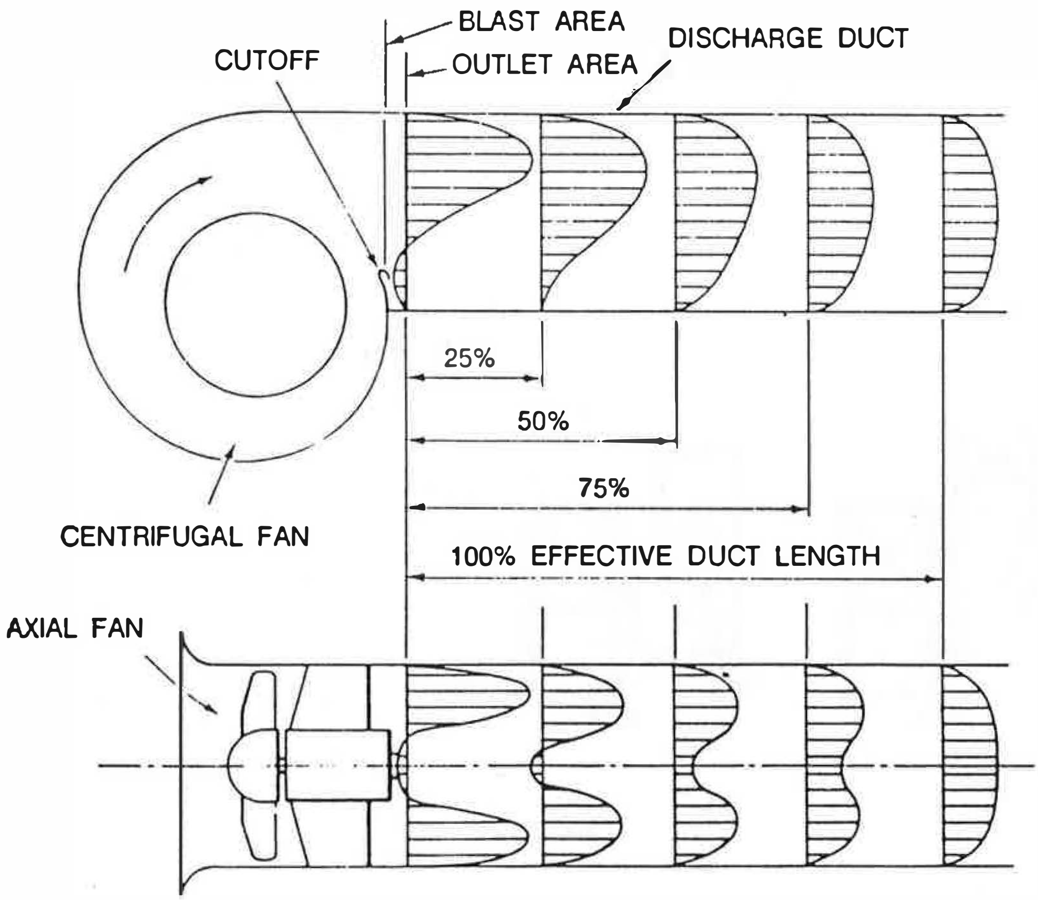


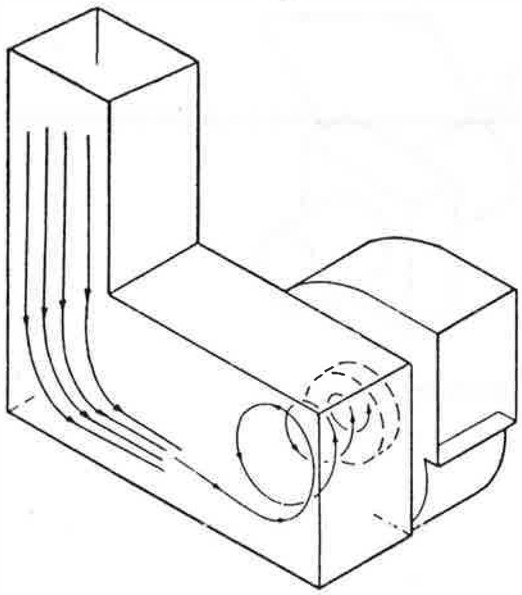
Fan A
N2
Fan A
N1
Static Pressure (Ps)
Ps2
Ps1
2
1
4
3
BHP2
BHP1
Brake Horsepower
N2
N1
0
Q1
Q2
Air Flow Rate (Q)

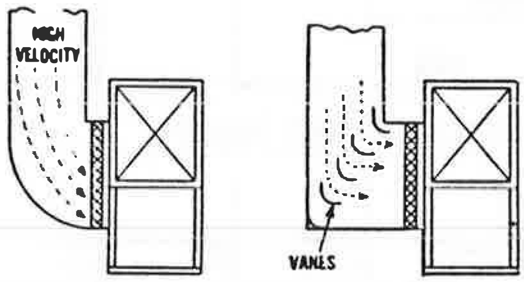


DUCT SYSTEM A
PRESSURE
PRESSURE
H
H
133%
100
50
0
1
2
FAN SPEED (N)
FAN SPEED (N × 1.10)
110%
PERCENT OF DUCT SYSTEM RESISTANCE
160
140
120
100
80
60
40
20
0
PERCENT OF POWER - H
0
20
40
60
80
100
120
140
160
180
200
PERCENT OF DUCT SYSTEM VOLUME FLOW - Q

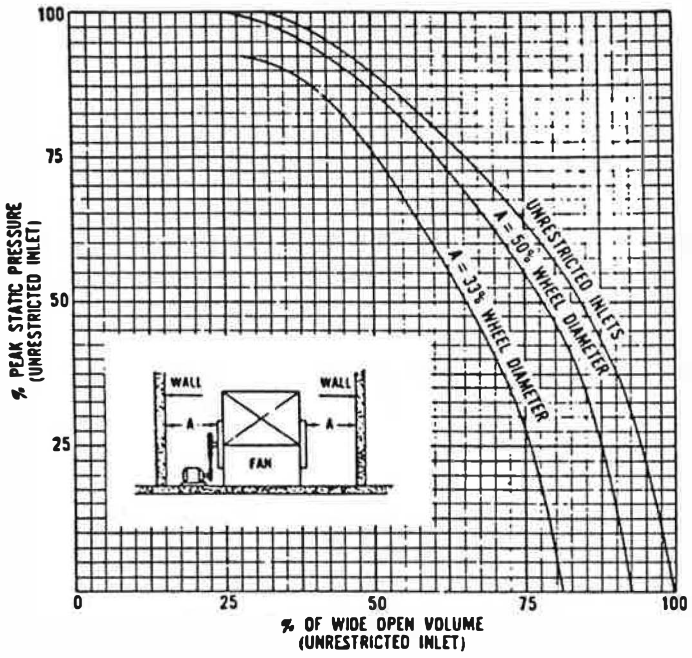

NOTE FAN INLET AREA EQUALS FAN OUTLET AREA
FAN
DUCT SECTION D
SYSTEM COMPONENT B
SYSTEM COMPONENT E
DUCT SECTION C
DUCT SECTION A
DUCT SECTION F


BLAST AREA
DISCHARGE DUCT
CUTOFF
OUTLET AREA
25%
50%
75%
CENTRIFUGAL FAN
100% EFFECTIVE DUCT LENGTH
AXIAL FAN





POOR GOOD


100
75
50
25
% PEAK STATIC PRESSURE
(UNRESTRICTED INLET)
UNRESTRICTED INLETS
A = 50% WHEEL DIAMETER
A = 33% WHEEL DIAMETER
WALL
A
FAN
WALL
A
0
25
50
75
100
% OF WIDE OPEN VOLUME
(UNRESTRICTED INLET)

DUCTED FAN EFFICIENCIES

MODEL	TYPE	MOTOR LOCATION	FAN INPUT W	AIR FLOW m3/h	AIR FLOW L/s	AIR PRESSURE Pa	FAN OUTPUT W	FAN EFFICIENCY	COMMENTS
MANUFACTURER: SPENCER									
CMV 125	CENTRIFUGAL	EXTERNAL	100	465	129.2	500	64.58	64.58%	
CMV 280	CENTRIFUGAL	EXTERNAL	1800	7900	2194	600	1316.67	73.15%	
MANUFACTURER: VICTORIA FAN									
244/4-8/45/3H	AXIAL	INTERNAL	2.24	180	50	23.75	1.19	53.01%	BIFURCATED, 900 RPM
244/4-8/45/3H	AXIAL	INTERNAL	2.61	90	25	30	0.75	28.74%	BIFURCATED, 2810 RPM
294/4-8/45/3H	AXIAL	INTERNAL	216.3	2160	600	240	144.00	66.57%	BIFURCATED, 1400 RPM
294/4-8/45/3H	AXIAL	INTERNAL	27.6	900	250	58.75	14.69	53.22%	BIFURCATED, 900 RPM
294/4-8/45/3H	AXIAL	INTERNAL	10.82	180	50	45	2.25	20.79%	BIFURCATED, 900 RPM
394/8/45/3H	AXIAL	INTERNAL	43.27	1800	500	45.75	22.88	52.87%	BIFURCATED, 900 RPM
394/8/45/3H	AXIAL	INTERNAL	134.28	1800	500	115	57.50	42.82%	BIFURCATED, 1400 RPM
594/10/45/3H	AXIAL	INTERNAL	328.24	2340	650	250	162.50	49.51%	BIFURCATED, 1400 RPM
MANUFACTURER: HAMILTON STANDARD									
MFF DST	MIXED FLOW	INTERNAL		900	250	1825	456.25	73.00%	AT 7000 RPM, 10 BLADES
IMV	AXIAL	INTERNAL		540	150	225	33.75	70.00%	AT 7765 RPM, 5-6 BLADES

DUCTED FAN/MOTOR EFFICIENCIES

MODEL	TYPE	MOTOR TYPE	MOTOR LOCATION	MOTOR VOLTAGE	MOTOR INPUT W	AIR FLOW m3/h	AIR FLOW L/s	AIR PRESSURE Pa	FAN/MOTOR OUTPUT W	FAN/ MOTOR EFFICIENCY	COMMENTS
MANUFACTURER: EBM*											
G2E 180-AA 03-01	CENTRIFUGAL	CAPACITOR	INTERNAL	220	300	535	148.6	550	81.74	27.25%	SINGLE INLET, SCROLL HSG, DIE CAST ALUM.
G2S 108-CD 02-01	CENTRIFUGAL	S. POLE	INTERNAL	220	57	150	41.67	50	2.08	3.65%	SINGLE INLET, SCROLL HSG & IMPELLER
D2E 097-BD 04	CENTRIFUGAL	CAPACITOR	INTERNAL	220	75	390	108.3	25	2.71	3.61%	DOUBLE INLET, SCROLL HSG & IMPELLER
D2E 133-DB 01	CENTRIFUGAL	CAPACITOR	INTERNAL	220	175	710	197.2	100	19.72	11.27%	DOUBLE INLET, SCROLL HSG & IMPELLER
G2E 140-AL 40-01	CENTRIFUGAL	CAPACITOR	INTERNAL	220	125	420	116.7	100	11.67	9.33%	SINGLE INLET, SCROLL HSG, DIE CAST ALUM.
G2E 160-AD 01-01	CENTRIFUGAL	CAPACITOR	INTERNAL	220	250	610	169.4	40	6.78	2.71%	SINGLE INLET, SCROLL HSG, DIE CAST ALUM.
MANUFACTURER : AIRFLOW											
52BTXL	CENTRIFUGAL	PERMANENT, SPLIT CAPAC., 2 POLE	EXTERNAL	220	115	325	90.28	210	18.98	16.49%	SINGLE INLET FAN
57 BXL	CENTRIFUGAL	PERMANENT, SPLIT CAPAC., 2 POLE	EXTERNAL	220	160	380	100	245	24.60	15.31%	SINGLE INLET FAN
76 E2WU4	CENTRIFUGAL	PERMANENT, SPLIT CAPAC., 4 POLE	EXTERNAL	220	300	487	135.3	125	16.91	5.64%	DOUBLE INLET, MTR IN ONE INLET
83 F2WL	CENTRIFUGAL	PERMANENT, SPLIT CAPAC., 4 POLE	EXTERNAL	220	170	1270	352.8	58	20.46	12.04%	DOUBLE INLET, MTR IN ONE INLET
83 F2WXL	CENTRIFUGAL	PERMANENT, SPLIT CAPAC., 6 POLE	EXTERNAL	220	130	1150	319.4	63	20.13	15.48%	DOUBLE INLET, DOUBLE WIDTH
90 G2WL	CENTRIFUGAL	PERMANENT, SPLIT CAPAC., 4 POLE	EXTERNAL	220	700	525	145.8	200	29.17	4.17%	DOUBLE INLET, DOUBLE WIDTH
102 H2WL	CENTRIFUGAL	PERMANENT, SPLIT CAPAC., 6 POLE	EXTERNAL	220	600	900	250	125	31.25	5.21%	DOUBLE INLET, DOUBLE WIDTH
40 BTX	CENTRIFUGAL	2 POLE	EXTERNAL	220	100	75	20.83	75	1.58	1.56%	DUPLEX FANS, 1 MTR, TWO FANS
45 C2T	CENTRIFUGAL	4 POLE	EXTERNAL	220	62	175	48.61	38	1.85	2.98%	DUPLEX FANS, 1 MTR, TWO FANS
52 D2TX	CENTRIFUGAL	PERMANENT, SPLIT CAPAC., 4 POLE	EXTERNAL	220	130	310	86.11	50	4.31	3.31%	DUPLEX FANS, 1 MTR, TWO FANS
MANUFACTURER: ADVANCED DESIGN & MANUFACTURE											
INDUX ILF300	AXIAL	EXTERNAL ROTOR CAP. START	INTERNAL	220	175	150	41.67	405	16.876	9.64%	INLINE DUCT FAN
					223	750	208.3	235	48.96	21.95%	INLINE DUCT FAN
MANUFACTURER: WOODS FANS											
6J	AEROFOIL	INFORMATION NOT PROVIDED	INTERNAL	230	22	180	50	10	0.50	2.27%	ADJUSTABLE PITCH AEROFOIL
6J	AEROFOIL	INFORMATION NOT PROVIDED	INTERNAL	230	41.4	360	100	25	2.50	6.04%	ADJUSTABLE PITCH AEROFOIL
7J	AEROFOIL	INFORMATION NOT PROVIDED	INTERNAL	230	126.5	720	200	75	15.00	11.86%	ADJUSTABLE PITCH AEROFOIL
9J	AEROFOIL	INFORMATION NOT PROVIDED	INTERNAL	230	333.5	1620	450	75	33.75	10.12%	ADJUSTABLE PITCH AEROFOIL
12K	AEROFOIL	INFORMATION NOT PROVIDED	INTERNAL	230	575	1800	500	200	100.00	17.39%	ADJUSTABLE PITCH AEROFOIL
15J	AEROFOIL	INFORMATION NOT PROVIDED	INTERNAL	230	1357	5400	1500	200	300.00	22.11%	ADJUSTABLE PITCH AEROFOIL
12/33	AEROFOIL	INFORMATION NOT PROVIDED	INTERNAL	230	287.5	1584	440	25	11.00	3.83%	FIXED PITCH BIFURCATED
AXCENT 2, MX31	MIXED FLOW	INFORMATION NOT PROVIDED	EXT.BELT	400	508	2160	600	250	150.00	29.53%	INLINE MIXED FLOW
ILC 1	AXIAL	INFORMATION NOT PROVIDED	INTERNAL	230	46	136.8	38	50	1.90	4.13%	INLINE CENTRIFUGAL FAN
ILC 3	AXIAL	INFORMATION NOT PROVIDED	INTERNAL	230	94.3	352.8	98	100	9.80	10.39%	INLINE CENTRIFUGAL FAN
MANUFACTURER: WATER FURNACE											
AT	CENTRIFUGAL	ECM	INTERNAL	120	300	3420	950	82	77.90	25.97%	USED IN GROUND SOURCE H.P.'s
					400	5760	1600	167	267.20	66.80%	USED IN GROUND SOURCE H.P.'s

** These fans are all rated at their minimum acceptable static pressure as no other data was available. Efficiencies may be higher at higher statics.*