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# Efficient Air-Conditioning System Design to Improve Indoor Air Quality without Energy Penalty

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## ABSTRACT

*Outside air ventilation is important to indoor air quality. It is used to control the buildup of contaminants in the space by displacing some contaminated air with clean outdoor air to reduce the concentration of contaminants to an acceptable level. Because outdoor air is generally hot and humid in the tropics, the cost of air-conditioning increases sharply as the quantity of outdoor air brought into a building increases.*

*Recent studies have shown that indoor air is most often more contaminated than outdoor air, and as energy conservation has become increasingly important, indoor air quality has become a concern. Some buildings have experienced indoor air quality problems, resulting from inadequate outdoor air ventilation. While a higher percentage of outdoor air can help to resolve these problems, it will result in high energy costs.*

*To resolve the conflicting goals of indoor air quality and energy conservation, an air-conditioning system is proposed that integrates an energy recovery unit (rotary air-to-air energy exchanger) to precool the outdoor air admitted to the building using the energy available in the building exhaust air. This will result in a lower precooled outdoor air enthalpy. Mixing this precooled outdoor air with the return air allows a much larger quantity of outdoor air to be introduced into the building without an energy penalty.*

*This paper examines the use of an energy recovery unit in the air-conditioning system and presents a detailed analysis of potentially increased ventilation by using this technique.*

## INTRODUCTION

Indoor air quality in an air-conditioned environment is a matter of increasing concern. Occupied buildings rely on ventilation (the exchange of indoor air for outdoor air) to help maintain acceptable concentrations of pollutants such as fumes, odors, microorganisms, and other irritants, emanating from construction materials, furnishings, and occupants. These pollutants, which would otherwise be purged from a building, tend to be retained within buildings with limited ventilation. It is important that the conditioned air furnished to a space has an adequate ratio of outdoor air to dilute these contaminants as much as possible.

Many investigators have reported that the consequence of not achieving adequate ventilation is the sick building syndrome. A sick building affects not only the health of its occupants, but office productivity as well. If building occupants are satisfied with the indoor environment, health complaints are fewer, absenteeism decreases, and the workplace is generally more productive.

The key to improving indoor air quality is increasing outdoor air ventilation rates to dilute the contaminants. However, increased ventilation rates pose an additional load on the air-conditioning system. Additional energy is required to cool the ventilation air, and this is becoming increasingly important as energy costs rise.

A new approach aimed at resolving the conflict between energy conservation and the need for ventilation for health is presented in this paper. The basic principle of the design is the integration of an energy recovery unit in the air-conditioning system to dilute contaminants in the indoor air economically without compromising energy efficiency.

The method proposed to reduce the energy requirements associated with ventilation is to minimize the amount of air leakage through the building envelope, mechanically supply outdoor air and exhaust air of an approximately equal amount to and from the building, and incorporate a rotary air-to-air energy exchanger in the air-conditioning system to conserve energy by an energy transfer between incoming and outgoing airstreams. This results in a lower precooled outdoor air enthalpy. Therefore, more outdoor air can be introduced through the energy recovery unit in the proposed system before the enthalpy of its mixed air condition would exceed that of the system without energy recovery. This will allow a much larger quantity of outdoor air to be introduced into the building without an energy penalty.

Various types of heat exchangers are available, such as a rotary air-to-air energy exchanger wheel, a plate-type heat exchanger, a heat pipe heat exchanger, and a run-around coil system. After all available heat exchangers were examined, it was found that the rotary air-to-air energy exchanger wheel had good heat transfer efficiency and could recover both sensible and latent heat. In the core of the energy exchanger, energy is transferred from the

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warmer airstream to the cooler airstream without the two airstreams mixing; thus, the supply airstream is precooled before it enters the air-conditioned space.

The system allows a greater amount of room air to be exhausted and a corresponding amount of outdoor air to be introduced through the energy recovery unit without increased energy costs, for the following reasons:

• With energy recovery capability, the cooling efficiency of the outdoor air can be increased significantly. Compared to a conventional system without energy recovery, the amount of cooling required for the additional amount of outdoor air is reduced substantially. The energy required to condition the additional quantities of outdoor air is therefore substantially reduced.

• The "free" cold energy recovered from the air that was previously exhausted can be used to condition more outdoor air without increased energy consumption.

The increased ventilation provided by the energy recovery system is a valuable asset to the consulting engineer.

In this paper, the proposed system configuration is described. The effect of heat exchanger effectiveness and outdoor air enthalpy on system performance will be investigated, and a detailed analysis of potential increased ventilation by using the proposed system is presented.

## SYSTEM DESCRIPTION

### Conventional System

A typical air-conditioning system is shown schematically in Figure 1a; its psychrometric representation is shown in Figure 1b. The return air (RA) at state 2 and outdoor air (OA) at state 1 are mixed to create the mixed air (MA) at state 3. The mixed air is cooled at the cooling coil to supply air (SA) to the air-conditioned space at state 4. The amount of room air returned to the air-handling unit is equal to the amount of supply air less the amount of outdoor air. The remainder of supply air, which is equal to the amount of outdoor air, is lost to the outside.

### Proposed System

A schematic diagram of the proposed system is shown in Figure 2a; its psychrometric representation is shown in Figure 2b. An energy recovery system is incor-

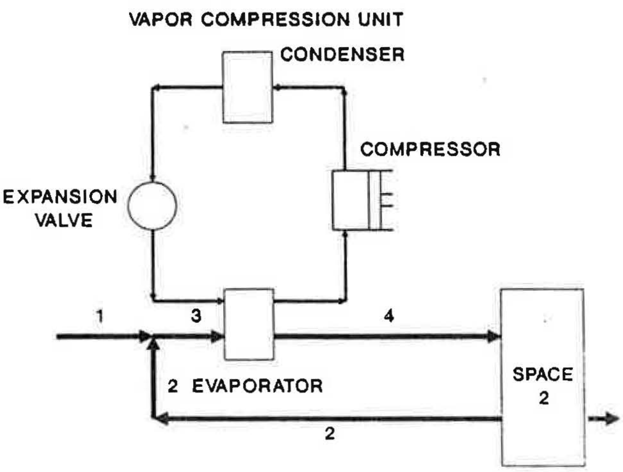


*Figure 1a* *Conventional air-conditioning system schematic*

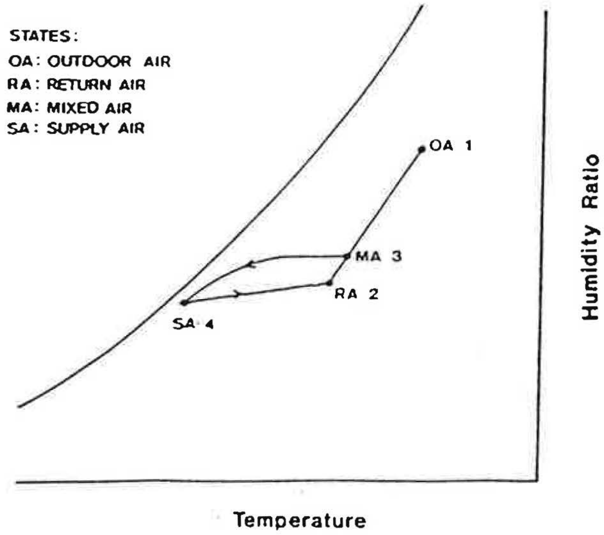


*Figure 1b* *Conventional system psychrometrics*

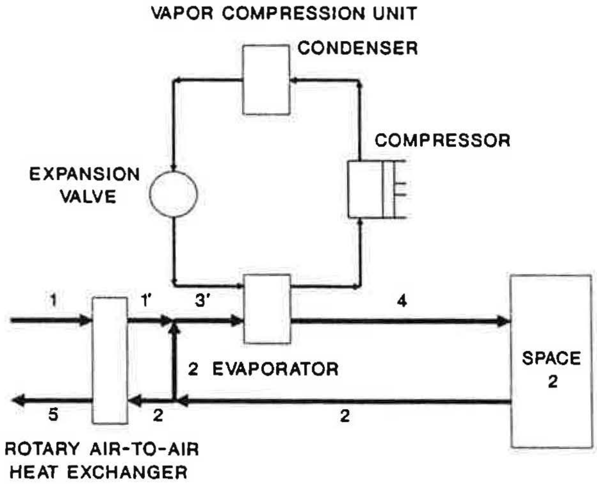


*Figure 2a* *Proposed air-conditioning system schematic (with energy recovery)*

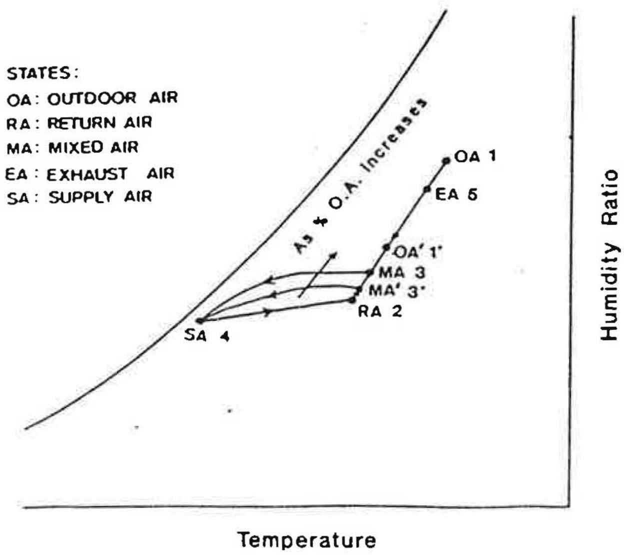


*Figure 2b* *Proposed system psychrometrics*

porated. A certain amount of used air from the room is exhausted to the outside in order to make room for outside ventilation air. The used air is close to the desired comfort conditions, whereas the incoming air may be far from the desired humidity and temperature conditions. The energy recovery system extracts energy from the cool, dry used air and uses it to cool and dehumidify incoming fresh air.

For this purpose, the core of the energy recovery system consists of a rotary air-to-air total energy exchanger wheel. It has a revolving cylinder filled with an air-permeable medium with a large internal surface area. One-half of the rotor is connected to the outside airstream, and the other half to the exhaust airstream. The incoming and outgoing airflows travel counterflow for more effective energy transfer. The thermal wheel has a metallic base to promote sensible heat transfer; it is impregnated with desiccant for transferring latent energy. It is operated on the regeneration principle of heat exchange between the outside airstream and the exhaust airstream.

Sensible heat is transferred as the medium picks up and stores heat from the hot airstream and gives it up to the cold one. Latent heat is transferred as the medium (1) condenses moisture from the airstream with the higher humidity ratio (by means of adsorption), with a simultaneous release of heat; and (2) releases the moisture through evaporation (and heat pickup) into the airstream with the lower humidity ratio; thus, the moist air is dried while the dry air is humidified.

Both sensible and latent heat transfer occur simultaneously. The outside airstream is constantly preconditioned by the exhaust airstream. The efficiency of the energy wheel can vary from 60 to 80%, depending on the type of surface employed, the face velocity, and other design features.

**Model of Rotary Air-to-Air Energy Exchanger**

The energy exchanger was modelled by an effectiveness defined as the ratio of actual heat transfer to the thermodynamically limited maximum heat transfer with an infinite transfer area.

$$Eff = (H_{h,i} - H_{h,o})/(H_{h,i} - H_{c,i}) = (H_{c,o} - H_{c,i})/(H_{h,i} - H_{c,i})$$

or

$$H_{h,o} = Eff \times (H_{c,i} - H_{h,i}) + H_{h,i} \quad (1)$$

and

$$H_{c,o} = Eff \times (H_{h,i} - H_{c,i}) + H_{c,i} \quad (2)$$

## THEORETICAL ANALYSIS

The fundamental equations governing the mixing of outdoor air and return air are the conservation of energy and conservation of mass.

Energy balance:

$$M_{oa} \times H_{oa} + M_{ra} \times H_{ra} = M_{ma} \times H_{ma}$$

Air mass balance:

$$M_{oa} + M_{ra} = M_{ma}$$

By eliminating $M_{ra}$:

$$H_{ma} = p \times H_{oa} + (1 - p) \times H_{ra} \quad (3)$$

or

$$p = (H_{ma} - H_{ra}) / (H_{oa} - H_{ra}) \quad (4)$$

*where*

$$p = \text{percentage of outdoor air} = M_{oa}/M_{ma}$$

The amount of cooling required to go from the mixed air condition to the required off-coil condition depends on the enthalpy of the mixed air $H_{ma}$.

For the same value of $p$, Equation (3) shows that the enthalpy of the mixed air of the proposed system $H_{ma'}$ is lower than that of the conventional system because of its much lower precooled outdoor air enthalpy $H_{oa'}$. The difference in mixed air enthalpy of the proposed system and the conventional system, which represents the savings in cooling energy of the new system over the conventional system, is given by [from Equation (3)]:

$$DH = H_{ma} - H_{ma'} = p \times (H_{oa} - H_{oa'})$$

As more outdoor air is added to the mixed airstream, its enthalpy will increase. The amount of outdoor air that can be introduced before the enthalpy exceeds that of the conventional system is given by [from Equation (4)]:

$$p' = (H_{ma} - H_{ra}) / (H_{oa'} - H_{ra})$$

From Equation (1):

$$H_{oa'} = H_{oa} - Eff \times (H_{oa} - H_{ra})$$

Conventional system:

$$H_{ma} = p \times H_{oa} + (1 - p) \times H_{ra}$$

Proposed system:

$$H_{ma'} = p' \times H_{oa'} + (1 - p') \times H_{ra} = p' \times H_{oa} - p' \times Eff \times (H_{oa} - H_{ra}) + (1 - p') \times H_{ra}$$

1. To find the percentage of outdoor air $p'$ that can be achieved without incurring extra cooling energy—

For $M_{ma} \times (H_{ma} - H_{sa}) = M_{ma'} \times (H_{ma'} - H_{sa'})$

$M_{ma'} = M_{ma}$ ; $H_{sa'} = H_{sa}$

Therefore, $H_{ma'} = H_{ma}$

$$p' \times H_{oa} - p' \times Eff \times (H_{oa} - H_{ra}) + (1 - p') \times H_{ra} = p \times H_{oa} + (1 - p) \times H_{ra}$$

After simplifying, $p' = p / (1 - Eff)$ (5)

It can be seen that $p'$ is not affected by the outside air conditions.

2. To find the percentage of outdoor air $p''$ that can be achieved without increase in total energy use—

The new system requires additional parasitic power $d_{Ps}$ by the fans to move the air through the heat wheel. In order for the new system to operate without an increase in total energy use, its mixed air enthalpy should be $H_{ma} - dH$, such that $dH$, when converted to energy savings, can offset the increase in parasitic power.

$$dP_s = (M_{ma} \times dH) / \text{COP}$$

or

$$dH = (dP_s \times \text{COP}) / M_{ma}$$

where COP is the coefficient of performance of the vapor compression unit.

For $H_{ma'} = H_{ma} - dH$

$$p'' \times H_{oa} - p'' \times Eff \times (H_{oa} - H_{ra}) + (1 - p'') \times H_{ra} = p \times H_{oa} + (1 - p) \times H_{ra} - dH$$

After simplifying,

$$p'' = p/(1 - Eff) - dH/[(1 - Eff) \times (H_{oa} - H_{ra})] \quad (6)$$

It can be seen that $p''$ is affected by outdoor air conditions and the additional parasitic power.

## SYSTEM PERFORMANCE— A NUMERICAL EXAMPLE

To illustrate quantitatively the performance of the new system and to compare it with that of a conventional system, the following example is presented. Data are shown below.

Example Data

Area: Office building
Outdoor conditions:
Maximum load: 90°F (32.2°C) db, 80°F (26.7°C) wb
43.7 Btu/lb (84 kJ/kg) H
Minimum load: 78.8°F (26°C) db, 90% rh
40 Btu/lb (75 kJ/kg) H
Indoor conditions: 75°F (23.9°C) db, 60% rh
Supply airflow: 10,000 cfm (4720 L/s)
Ventilation: 10% (1000 cfm)
Supply air conditions: 56°F (13.3°C) db, 55°F (12.8°C) wb
Return airflow: 90% (9000 cfm)

The objective of the study is to find out how much more outdoor air the proposed system can introduce into the space as compared to the conventional system without (1) increased compressor power and, (2) increased total power (including parasitic power) under both the maximum outdoor air enthalpy condition and the minimum outdoor air enthalpy condition. Calculations were performed using a personal computer and a popular spreadsheet program.

## RESULTS AND ANALYSIS

The main objective of the study was to investigate potential increased ventilation resulting from the use of the proposed energy recovery system. Figure 3 shows the rate of cooling that could be recovered from 10% outdoor air by the air-to-air energy exchanger of various effectiveness. Figure 4 shows the amount of recovered energy that has to be converted to compressor power savings in order to offset the additional parasitic fan power.

The difference between the energy recovered and the amount required to offset the additional parasitic power is

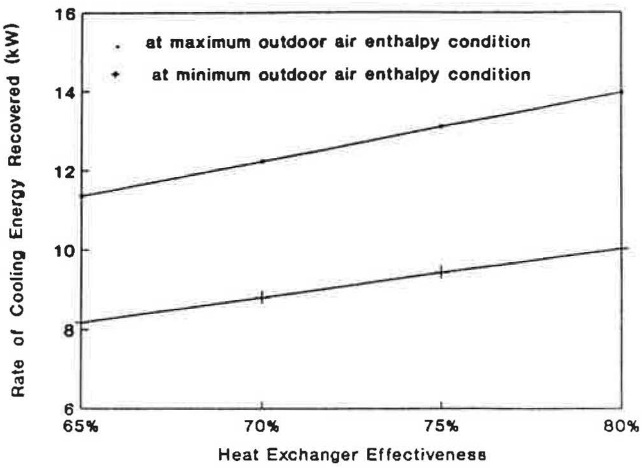


***Figure 3*** *Rate of cooling energy recovered from 10% outdoor air by air-to-air energy exchanger of various effectiveness*

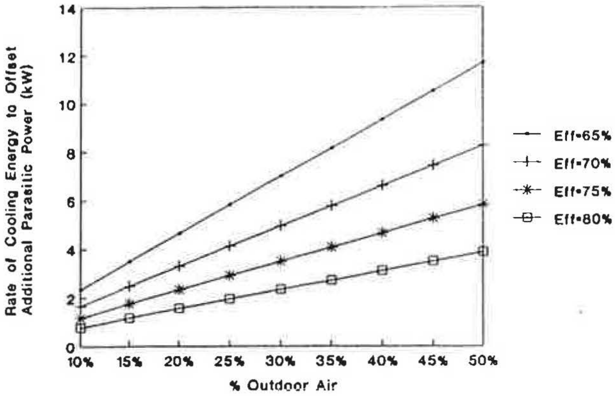


***Figure 4*** *Rate of cooling energy to be converted to compressor power savings*

the available "free energy." To study the effect of outdoor air on the energy consumption, the compressor power consumption and the total power consumption of both the conventional system and the proposed system are computed for various percentages of outdoor air at both the maximum outdoor air enthalpy and the minimum outdoor air enthalpy condition. For the conventional system, both the compressor power consumption and the total power consumption are a function of the percent outdoor air, outdoor air enthalpy, return air enthalpy, and the COP of the vapor compression unit. For the proposed system, the compressor power consumption is a function of the percent outdoor air, outdoor air enthalpy, return air enthalpy, COP of the vapor, compression unit, and the heat exchanger effectiveness.

The total power consumption also depends on the additional parasitic power of the heat recovery system. Figures 5a and 5b show the compressor power consumption versus the percentage of outdoor air for the conventional system and the proposed system of various heat exchanger effectiveness at the maximum outdoor air enthalpy and the minimum outdoor air enthalpy condition, respectively.

Figures 6a and 6b show the total power consumption versus the percentage of outdoor air for the conventional system and the proposed system at the maximum outdoor

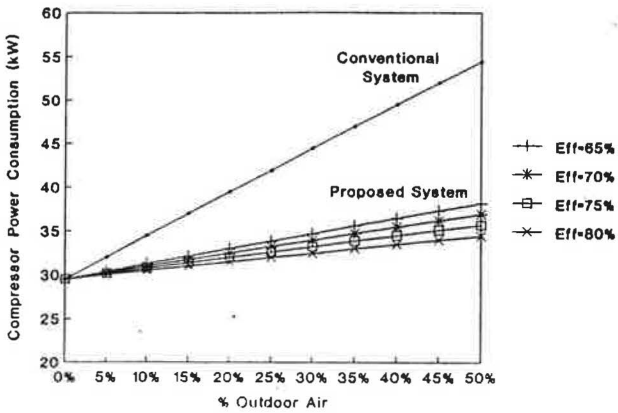


***Figure 5a*** *Compressor power consumption versus percentage outdoor air (maximum outdoor air enthalpy)*

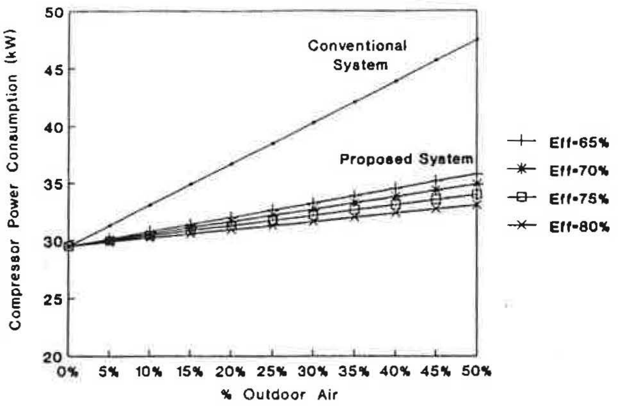


**Figure 5b** *Compressor power consumption versus percentage outdoor air (minimum outdoor air enthalpy)*

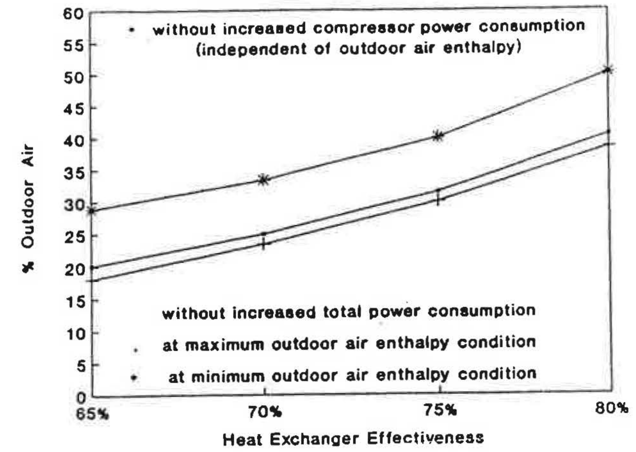


**Figure 7** *Performance of proposed system at various heat exchanger effectiveness*

air enthalpy and the minimum outdoor air enthalpy condition, respectively. It is evident that the gradient of the conventional system energy consumption line is far steeper than that for the proposed system, suggesting that the increase in the outdoor air ventilation rate has greater impact on the energy consumption for the conventional system than for the proposed system.

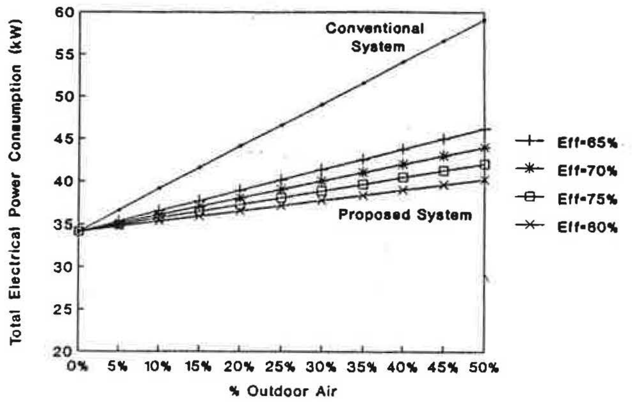


**Figure 6a** *Total eletrical power consumption versus percentage outdoor air (maximum outdoor air enthalpy)*

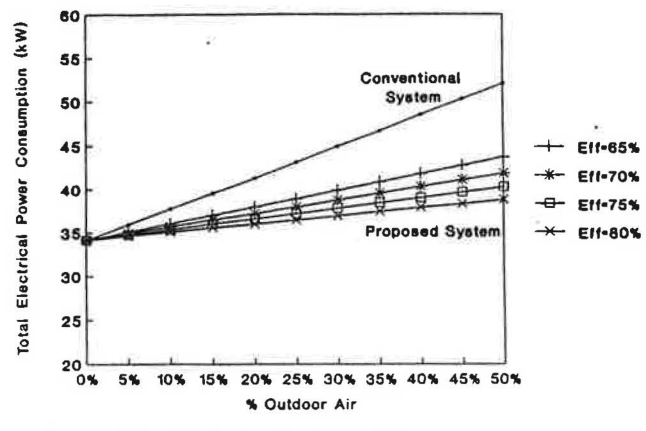


**Figure 6b** *Total electrical power consumption versus percentage outdoor air (minimum outdoor air enthalpy)*

From the charts, the amount of additional outdoor air the proposed system can introduce to the space without any increase in compressor power consumption or total power consumption at both the maximum outdoor air enthalpy condition and the minimum outdoor air enthalpy condition can be determined; the results are shown graphically in Figure 7.

The results compared to 10% outdoor air for the conventional system without energy recovery, are summarized below.

1. The percentage of outdoor air that can be achieved without increased compressor power consumption is not affected by outdoor air conditions [Equation (5)]. The amount ranges from 28 to 50% when the heat exchanger effectiveness varies from 65 to 80%.

2. The percentage of outdoor air that can be achieved without increased total power consumption is affected by outdoor air conditions [Equation (6)]. Under the maximum outdoor air enthalpy condition and the minimum outdoor air enthalpy condition, the proposed system can introduce 20 to 41% and 18 to 38% outdoor air, respectively, when the heat exchanger effectiveness varies from 65 to 80%.

From the results, it can be concluded that:

1. The heat exchanger effectiveness is a significant parameter on the performance of the proposed system.

2. The effect of outdoor air conditions on the performance of the proposed system is not significant in Singapore's context, as the variation in outdoor air enthalpy is relatively moderate.

3. The additional parasitic power in the heat recovery system does not affect the viability of the system.

4. With minimal additional parasitic power, the system can improve indoor air quality economically with air-to-air energy recovery.

## GENERAL ECONOMICS

It is difficult to quantify the benefits of increased outdoor air and indoor air quality. However, comparing the new system with the conventional system of the same outdoor air ventilation rate, the new system offers the following advantages:

1. Reduction of energy for refrigeration.

2. Reduction of cooling load, which reduces the

equipment size and thereby capital cost of cooling equipment (compressor, cooling tower, etc.), cooling coils, pumps, and piping.

It reduces the cost to such an extent that the savings significantly offset the capital cost of the heat recovery system. Sometimes, the use of energy recovery is the only means of stretching existing cooling equipment capacities to meet the needs of increased outdoor air to improve indoor air quality, without necessitating new cooling equipment.

As there are few moving parts in a heat recovery system, the additional maintenance cost is minimal as it is limited to only routine maintenance and periodic cleaning of the wheel surface.

## CONCLUSION

An energy-efficient air-conditioning system, where an energy recovery system is used to economically provide increased ventilation to improve air quality, has been investigated. An increase in the outdoor air supply rates for air-conditioned buildings can be achieved without an increase in energy consumption by the use of an air-to-air energy exchanger to recover the energy from exhaust air for preconditioning outdoor air. The results presented indicate that the proposed system can introduce 18 to 38% outdoor air as compared to the conventional system (10% outdoor air) without increased energy consumption, when the heat exchanger effectiveness varies from 65 to 80%. Air-to-air energy exchangers form an energy-efficient ventilation system.

In hot, humid climates, the proposed system contributes to a healthier indoor environment for people with more ventilation, without compromising on the energy economy. The energy recovery system can easily be retrofitted in an existing system, without having to upgrade the capacity of the existing equipment. The technique that can satisfy simultaneous needs for energy conservation and indoor air quality is a valuable asset to the design engineer.

## NOMENCLATURE

$M$ = mass flow rate, lb/s (L/s)
$H$ = enthalpy, Btu/lb (kJ/kg)
$Eff$ = effectiveness of heat exchanger
COP = coefficient of performance
$p$ = percentage of outdoor air to total supply air (conventional system)
$p'$ = percentage of outdoor air to total supply air achieved by the proposed system without increased compressor power
$p''$ = percentage of outdoor air to total supply air achieved by the proposed system without increased total power
$DH$ = difference in mixed air enthalpy between the conventional system and the proposed system, Btu/lb (kJ/kg)
$dH$ = portion of recovered energy to be converted to power savings to offset the additional parasitic power in the heat recovery system, Btu/lb (kJ/kg)
$P_s$ = parasitic fan power, kW

### Subscripts

$oa$ = outdoor air
$oa'$ = precooled outdoor air
$ra$ = return air
$ma$ = mixed air of conventional system
$ma'$ = mixed air of proposed system (mixture of precooled outdoor air and return air)
$sa$ = supply air
$h,i$ = heat exchanger hot side inlet air
$h,o$ = heat exchanger hot side outlet air
$c,i$ = heat exchanger cold side inlet air
$c,o$ = heat exchanger cold side outlet air

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