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Natural (Stack) Ventilation Augmented with Air-flow Induction Jets

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The inherent unreliability of the forces which drive natural ventilation can make such systems unattractive for the designer. Developing interest in mixed-mode ventilation is prompting difficulties in sourcing components suitable for ultra-low velocity flow generation in large ducts. This work examines the possibility of using air induction. A theoretical analysis generates equations which assist the designer in sizing a suitable inducer for ventilation purposes. Preliminary tests which verify the theory are described. Possible benefits include easier installation, use of widely available fans and low obstruction. Further work is needed to evaluate such benefits against the problems of low overall efficiency and potential noise nuisance.

Nomenclature

A = area (m^2)
h = the height of the top of the stack above the centre of the air inlet opening (m)
m = mass flow ($kg.s^{-1}$)
P = static pressure (Pa)
Po = total pressure (Pa)
ΔP = inducer pressure rise (Pa)
Δt = the inside – outside temperature difference.(^0C)
v = velocity ($m.s^{-1}$)
$\dot{V}$ = volumetric flow ($m^3.s^{-1}$)
W_i = minimum power needed to drive nozzle (W)
W_{min} = air power for total flow (W)
ε = entrainment ratio = $\frac{\dot{V}_2}{\dot{V}_1}$
η_i = induction nozzle efficiency
θ = duct/nozzle exit area ratio = $\frac{A_2}{A_1}$
ρ = density ($kg.m^{-3}$)

1.Background

Traditional mechanical ventilation systems require significant amounts of energy to circulate the air through ductwork systems and associated fittings. In air conditioned offices, around 19% of the total energy use is expended in moving air and water; in addition 10% of the energy is used by the refrigeration systems for air conditioning [1]. To reduce the energy consumption of buildings, designers are increasingly turning to natural ventilation. For more sophisticated buildings, e.g. the Inland Revenue Headquarters Building (as described in [2]) and the Queens Building at de Montfort University [3], ventilation stacks are included so that there is less dependence on a continuous prevalence of wind forces to drive the ventilation flows

The Queens Building has been the subject of many papers and articles, most of which are beyond the scope of this work. Ventilation measurements in the building conducted by Howarth et al [3] have demonstrated that the stack ventilation system works well in hot weather due to supplementary wind forces. Nevertheless there is a risk of a shortfall of fresh air flow at times when the external air temperature is close to the inside comfort temperature. Figure 1 shows a relevant sample of measurements in hot summer conditions for one of the building's auditoria. The three test flow rates were recorded when the inside temperature was lower than outside. Under these conditions, flow would be expected to occur in the reverse direction, i.e. down the stack. In view of the fact that flow direction is not identified in Fig 1 and that modeling techniques usually involve the square root of temperature difference, these values are all shown as positive. As the space was designed to accommodate up to 150 people who would require 1.2 m^3/s of air (at 8 l/s per person), it is clear that there are times when the air flow falls below the desired level. This results in a deterioration of air quality and an increased risk of overheating. At these times supplementary mechanically induced pressures would ensure a continuity of air flow at the required rate.

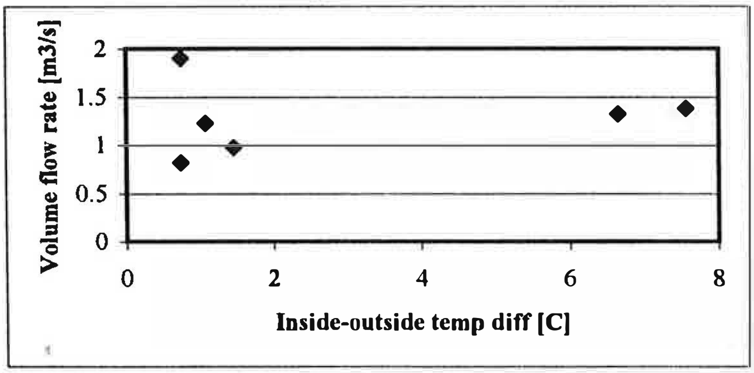

Fig 1 Summer air flows in a naturally ventilated auditorium

Heiselberg [4] has observed that present design philosophy is often based on two options; natural ventilation with passive cooling or mechanical ventilation and refrigeration, without considering a compromise approach which introduces just sufficient mechanical assistance to make the ventilation system work at all times. Indeed it is suggested that sustainable technologies are frequently rejected because of anxieties concerning their performance in extreme conditions. With mechanical assistance, the following additional benefits are achieved:-

stacks need not be so high (saving on capital and embodied energy costs)
inlets need not necessarily be at low level (near noise and pollution sources)
supply air and exhaust air can be routed close together so that a range of exhaust heat recovery devices may be incorporated

In a case study of a fan-assisted natural ventilation installation, Tjelflaat and Rodahl [5] comment on the problem of sourcing fans suitable for the low velocity, large cross section ducts and point to the need for the development of suitable devices. This paper has suggested a solution which employs available equipment.

Air flows generated by buoyancy and wind encounter low resistance in the large openings and flow tracts of naturally ventilated buildings. Mechanical assistance for air flows in these very large ducts with ultra low velocity can be provided with a very low power requirement. Again, using the example of the Queens Building where velocities rarely exceed 0.2 m/s, the measurements [3] have shown that a temperature difference of around 4.5 ^{0}C ensures a flow rate of 1.2 m^3/s through 17.6m stacks. The pressure rise available due to buoyancy effects can be estimated using the equation for stack pressure from the CIBSE Guide [6] and CIBSE Applications Manual AM10 [2].

$$\Delta p = 0.043h\ \Delta t \qquad (1)$$

Under the above conditions, a pressure of 3.4 Pa is therefore sufficient to overcome the friction of the inlet and exit flow tracts at the desired flow rate of 1.2 m^3/s. Thus, when large air flow tracts are made available, it is possible to augment, or even replace the natural forces with low powered alternative mechanical sources.

The addition of conventional axial or centrifugal fans is not straightforward because their presence in the flow path may significantly increase flow resistance, so impairing the performance of the natural ventilation system at times when the fan is not in use. Also it is common for the ventilation stacks to be of non circular cross section – the Queens building's stacks are of rhombic cross section. Thus, a conventional fan would require complex transition pieces.

This paper proposes the use of air inducers, or ejectors, as devices to enable conventional fans to be used in large natural ventilation tracts to enhance the airflow. Fig 2 shows an example of such a device. A flow of primary air is ducted from a conventional fan positioned outside the ventilation flow tract. The turbulent jet generated as the primary air is released induces air from the main ventilation duct and produces the secondary flow which enhances the natural ventilation forces.

The ejector may be installed in either the supply or extract duct – or both. When installed in the supply duct there is potential for more effectively exploiting any thermal storage during night ventilation by drawing the primary air through hollow building components in summer. In winter, the primary air may be pre-heated by making thermal contact with the exhaust air through a heat exchanger of the type described by Shao et al [7]. Ejectors installed in the exhaust duct may supply pre-heated air into the stack to provide additional buoyancy in hot weather. The air for the jet might be drawn from the duct itself, or it may be provided from another source. For example, air from a mechanical toilet extract system may provide assistance, using an inducer, for exhaust ventilation air from a naturally ventilated zone.

2. Air inducer theory

Figure 2 shows a cross section of an air powered induction system which uses a centrally positioned nozzle (1) to entrain a secondary air flow (2) within a natural ventilation duct. Neglecting buoyancy forces and frictional effects at the duct wall, a momentum balance across the induction section shown in Figure 2 yields:

$$P_3A_3 - P_1A_1 - P_2A_2 = \dot{m}_1 v_1 + \dot{m}_2 v_2 - \dot{m}_3 v_3 \qquad (2)$$

For subsonic flow at the exit plane of the nozzle; $P_2 = P_1$ (3)

Assuming the duct to be of constant cross sectional area then;

$$A_1 + A_2 = A_3 \qquad (4)$$

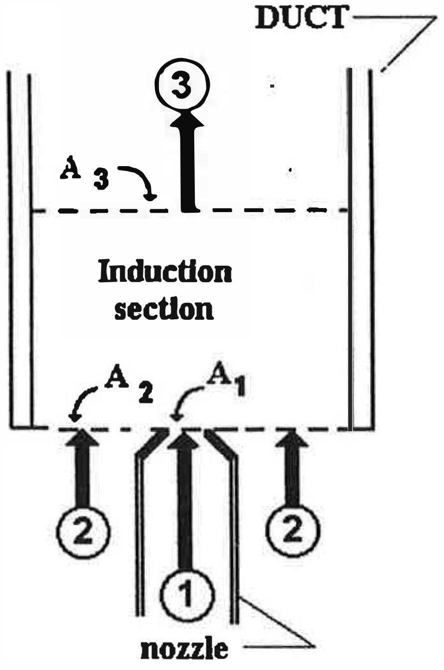

Figure 2: Model of induction system

Substituting (3) and (4) into (2) gives;

$$(P_3 - P_1)(A_1 + A_2) = \Delta P_{ind}(A_1 + A_2) = \dot{m}_1 v_1 + \dot{m}_2 v_2 - \dot{m}_3 v_3 \qquad (5)$$

Where ΔP_{ind} = the static pressure rise across the induction section.
From mass flow continuity:

$$v = \frac{\dot{m}}{\rho A} \qquad (6)$$

and

$$\dot{m}_3 = \dot{m}_1 + \dot{m}_2 \qquad (7)$$

Substituting (6) and (7) into (5) into the result gives:

$$\begin{aligned}\Delta P_{ind}(A_1 + A_2) &= \frac{\dot{m}_1^2}{\rho A_1} + \frac{\dot{m}_2^2}{\rho A_2} - \frac{(\dot{m}_1 + \dot{m}_2)^2}{\rho(A_1 + A_2)} \\ &= \frac{\dot{m}_1^2}{\rho A_1}\left(1 + \frac{(\dot{m}_2/\dot{m}_1)^2}{A_2/A_1} - \frac{(1 + \dot{m}_2/\dot{m}_1)^2}{1 + A_2/A_1}\right)\end{aligned} \qquad (8)$$

Defining secondary flow area ratio, $\theta = \frac{A_2}{A_1}$ and entrainment ratio, $\varepsilon = \frac{\dot{m}_2}{\dot{m}_1}$ and

noting that $\dot{m}_1^2 = \rho^2 A_1^2 v_1^2$, then following substitution and rearrangement,

$$\frac{\Delta P_{ind}}{1/2\rho v_1^2} = \frac{2}{1+\theta}\left(1 + \frac{\varepsilon^2}{\theta} - \frac{(1+\varepsilon)^2}{(1+\theta)}\right) \qquad (9)$$

Equation (9) describes the static pressure rise across the induction region non-dimensionalised by the velocity pressure of the driving flow at the inducer nozzle exit.

Assuming that the density of air remains constant then the ideal and therefore minimum, fan power required to move the total volume through a flue without an inducer is,

$$\dot{W}_{min} = \Delta P(\dot{V}_1 + \dot{V}_2) = \Delta P(1+\varepsilon)\dot{V}_1 \qquad (10)$$

The minimum power needed to drive the nozzle is,

$$\dot{W}_i = \dot{V}_1(1/2\,\rho\, v_1^2) \qquad (11)$$

Equation (11) assumes the flow through the nozzle is frictionless and the upstream kinetic energy is negligible compared with that at exit.

Defining the efficiency of an induction system as,

$$\eta_i = \frac{\dot{W}_{min}}{\dot{W}_i} \qquad (12)$$

Substituting Equations (10) and (11), cancelling like terms and substituting equation (9), then the theoretical efficiency of an inducer is given by,

$$\eta_i = 2\frac{(1+\varepsilon)}{(1+\theta)}(1+\frac{\varepsilon^2}{\theta} - \frac{(1+\varepsilon)^2}{(1+\theta)}) \qquad (13)$$

Equation (13) shows that for a given area ratio (θ) the efficiency of an inducer is a function of entrainment ratio (ε) only.

By differentiating Equation (13) with respect to ε, the value of entrainment ratio that maximises η_i for a given θ is,

$$\varepsilon_o = \frac{\theta - 2}{3} \qquad (14)$$

Where ε_o is the optimum entrainment ratio for a given θ. Substituting Equation (14) into (13) gives the theoretical maximum inducer efficiency for a given area ratio, (θ);

$$\eta_{i,max} = \frac{8}{27}(1+\frac{1}{\theta}) \qquad (15)$$

Substituting Equation (13) into (9) on rearrangement yields the dimensionless pressure rise created by an inducer of a given area ratio (θ) operating at its maximum efficiency defined by Equation (14), *vis*;

$$\frac{\Delta P}{1/2\,\rho\, v_1^2} = \frac{8}{9\theta} \qquad (16)$$

The proposed induction system can take a variety of forms. The example in Fig 2 shows a circular nozzle on the centre-line of the secondary duct. An alternative arrangement incorporates an annular jet discharging vertically along the wall of the secondary duct.

An example of the application would be to supply 0.24 m^3/s of air at a velocity of 30 m/s through a 100mm diameter nozzle in each of the exhaust stacks of the Queens Building. The induced flow would be 0.33 m^3/s giving a total of 0.57 m^3/s. The pressure rise generated would be 3.3 Pa with an air power requirement of 90 W and an efficiency of around 8%. In view of the small amounts of power involved and the energy transfer possibilities, this low value of efficiency may not be significant. However, also associated with the high primary air velocity is a potential noise nuisance. Further research is required to assess the magnitude of this potential problem.

3. Experimental Results

Preliminary tests have been conducted with the objective of verifying the above theory, using the rig shown in Fig 3. The spiral galvanised steel main (outer) duct is of diameter 315 mm and length 3 m. A smaller 100 mm inner duct runs concentrically through the large duct for a distance of 0.5 m and terminates with an interchangeable nozzle. Nozzles of diameters 47mm, 62 mm and 102 mm were used to provide jet velocities between 19 m/s and 26 m/s. A variable speed axial flow fan provided the flow through the inner duct.

The results are plotted in dimensionless form on Fig 4. The three curves show theoretical pressure rise vs entrainment ratio for area ratios 43.92 (47 mm diameter nozzle), 24.83 (62 mm diameter nozzle) and 8.54 (102 mm diameter nozzle). The limited number of results recorded in the preliminary tests are encouraging as they verify the theory (within +/-12 %).

4. Conclusions

A clear need for the augmentation of buoyancy and wind driven flows in naturally ventilated buildings has been identified. The induction system, using ejectors, has the following advantages:

- In common with any natural ventilation system using mechanical assistance the designer benefits with extra flexibiilty arising from reduced dependence on natural forces
- the inducer can be accommodated with the minimum of obstruction to flow (especially in annular form)
- readily available fan units can be used

Although design equations have been derived and validated by experiment further research is required to quantify the benefits and assess the implications of the low efficiency and potential noise problems.

5. References

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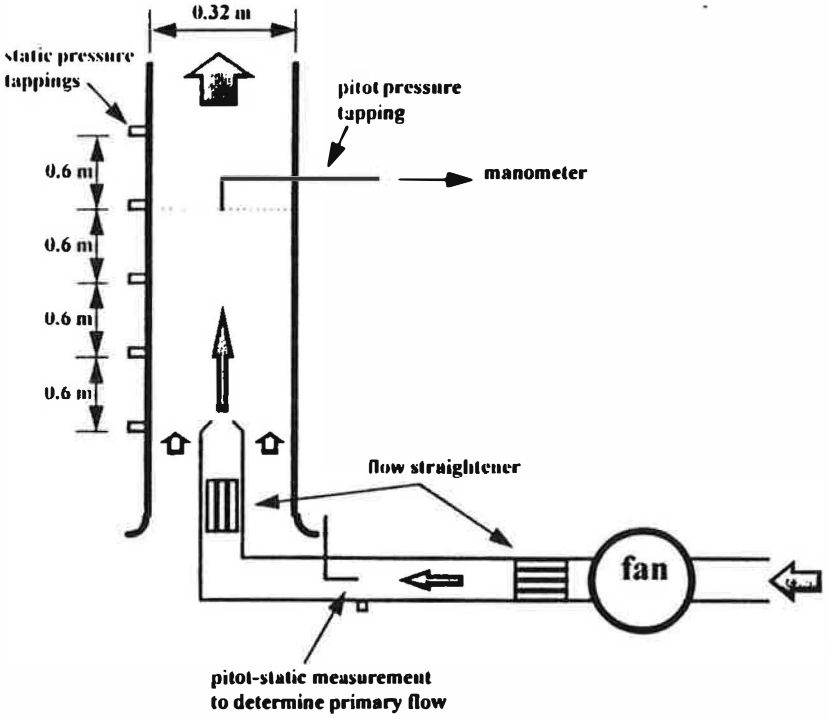

Figure 3: Schematic diagram of air induction test rig

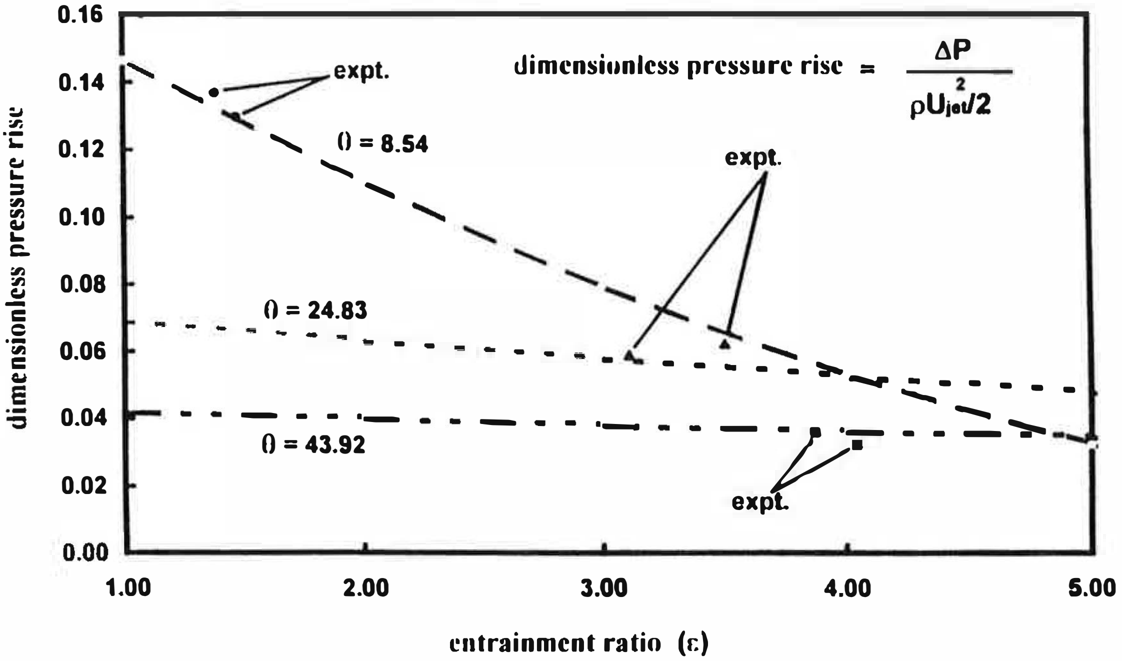

Figure 4: Variation in dimensionless pressure rise with entrainment ratio