Interaction Between Flow Elements in Large Enclosures

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PAPER NO. 44

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SUMMARY

Several sources for the air movement in large enclosures as for example diffusers, pressure difference around the construction, cold downdraugth and thermal plumes make it difficult to use simplified design methods for the air distribution system as the methods based on throws of jets and penetration depths of non-isothermal jets.

When those different flow elements at the same time occur in a room they will influence each other and the air flow pattern will depend on the individual strength of each element and the way they act together.

The results of model experiments show that the penetration depths and the paths of cold jets in enclosures are not influenced by the presence of distributed heat sources and only slightly influenced by the presence of concentrated heat sources. However, different locations and different strengths of a heat source in an enclosure may result in quite different air flow patterns. It is therefore necessary in cases with heat sources in an enclosure to take the flow from these air movement sources into account in the design procedure of efficient ventilation systems.

INTERACTION BETWEEN FLOW ELEMENTS IN LARGE ENCLOSURES

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INTRODUCTION

Air distribution in ventilated rooms is a flow process which consists of several flow elements such as supply air jets, exhaust flows, thermal plumes, boundary layer flows and infiltration. The simplified design methods for each of these flow elements are very useful in situations where the airflow pattern in a room is dominated by a single flow element or by flow elements which are not interacting with each other. In displacement ventilation the supply of air from a low level diffuser and the thermal plume from a heat source above the floor are a good example of an air distribution system with different flow elements which do not influence each other.

Air distribution with inclined jets is widely used in large enclosures when warm or chilled air is supplied through grilles and nozzles. In many of these large enclosures where a complicated geometry often is present different flow elements will occur at the same time and they might influence the flow path of each other. The air flow pattern in the enclosure will depend on the individual strength of each element and on the way they act together. It is therefore necessary in the design procedure for the air distribution system not only to determine the jet trajectories but at the same time to take all air movement sources into account, to estimate if the interaction between the flow elements changes the flow path of the individual elements and to estimate if this affects the air flow pattern and the efficiency of the ventilation system.

In this paper experiments in a scale model are used as a first attempt to investigate how different flow elements such as supply air jets, thermal plumes and free convection flows interact with each other in a large enclosure, if the path of each individual flow element changes and if this influences the overall air flow pattern in the enclosure. The main emphasis has been put on the pathways of chilled free air jets and whether the convective flows from both distributed and concentrated heat sources affect the pathway of the jet and the air flow pattern in the enclosure as a function of the location of the heat source and as a function of the heat supplied by the source.

TRAJECTORY OF A NON-ISOTHERMAL FREE AIR JET

The trajectory of a horizontal projected non-isothermal free jet can be described by equation (1). The trajectory coordinates are defined as the geometrical place of the points where the mean values of the velocities and temperatures reach their maximum in the vertical cross sections of the jet.

$$\frac{y}{\sqrt{A_o}} = \psi \frac{k_2}{k_1^2} Ar_o \left(\frac{x}{\sqrt{A_o}} \right)^3 \qquad (1)$$

The equation is based on analytical studies and has been verified by experiments by several authors. Zhivov, [1], concluded from the large dispersion of results in the literature and from experimental data from different authors that the following values of the coefficients were suitable:

$\psi = 0.47$; $k_1 = 6.5$; $k_2 = 5.0$

Equation (1) then becomes:

$$y = 0.0019 \frac{\Delta t_o A_o}{u_o^2} \left(\frac{x}{\sqrt{A_o}} \right)^3 \qquad (2)$$

The behaviour of a non-isothermal jet discharged into the open space is predicted rather well with the above equation. However, Murakami, [2], has shown that it is not always possible by the equation to predict the trajectory of a jet discharged into an enclosed space. The reason is that in an open space the air temperature around the jet is uniform while there often is a vertical temperature distribution in an enclosed space. When there is a temperature gradient the temperature in the lower part of the space differs from the temperature in the upper part and the temperature difference between the jet and its surroundings becomes thereby smaller in the lower part. The chilled air jet in an enclosure will therefore not fall as rapidly as it would be the case in an open space with uniform temperature.

SCALE MODEL AND SIMILITUDE

Scale model experiments are one of the methods that can be used to determine the air distribution in large spaces. In scale model experiments it is necessary to ensure that the physical processes occuring in the scale model represent those in the building to an acceptable degree of accuracy. The conditions for model experiments are therefore formulated from the governing equations in a nondimensional form and exact correspondence is achieved by maintaining the important dimensionless parameter groups constant which characterize fluid flow and heat transfer in enclosures. In practice in complex cases of thermal flow processes this cannot be entirely fulfilled, however, within certain ranges of flow conditions it is not necessary. At a sufficiently high level of velocity the structure of the turbulence, the air flow pattern and the heat transfer will be similar at different velovity levels and therefore independent of the Reynolds and Rayleigh numbers. Therefore, for approximate modelling of the processes in which forced flow and natural convection occur it is sufficient to maintain the Archimedes number constant and the Reynolds and Rayleigh numbers above certain critical values.

$$Ar = \text{identical}; \quad Re \gg Re_c; \quad Ra \gg Ra_c$$

Mierzwinski, [3], reports some results from jet tests in models and he concludes that quasi-stabilization of the mean velocity profiles in jets occurs when Re = 2000 - 4000 depending on the size of the model. Fissore, [4], reports that for analysis of air jets deflection a critical Reynolds number of $Re_c = 1850$ is adequate. Reynolds number independence for secondary flows, ventilation efficiency etc. occur at much higher Reynolds numbers, [3, 5, 6]. At modelling of natural convection phenomenon turbulent convection flow occur when $Ra = 10^6 - 3.3 \cdot 10^8$.

The scale model experiments were performed in a model with the dimensions (length x width x height) 1.41 m by 0.71 m by 1.41 m. The circular air supply opening was positioned in the middle of one of the narrow walls and had an area of $A_o = 0.00442$ m^2. The cicular air exhaust opening was positioned above the supply opening just beneath the ceiling and had the same area. The supply air jet is regarded as being free from Coanda-effects from walls etc. For visualising purposes the front wall was constructed of double glass. Except for the short period of taking photographs the glazed wall was covered with isolation material. All other walls were isolated.

Two types of heat sources were used. The first type was a distributed heat source consisting of a electrically heated panel on the floor. The panel was divided into two individual zones which made it possible to use three different heat sources. Type a: the whole floor heated, type b: half of the floor close to the supply heated and type c: half of the floor far from the supply heated. The second type was a concentrated heat source, type d: consisting of a heating wire twisted around an isolated core. The heat source dimensions (diameter x height) were 0.04 m by 0.16m.

The total amount of tests in the measurement series was about 60. For each type of distributed heat source, type a-c, tests were run at three different supply air flow rates and for each air flow rate at 4-5 different power outputs from the source. For the concentrated heat source tests were run at a constant supply air flow rate with the source at three different locations in the centre plane of the enclosure and for each location at 4-5 different power outputs from the heat source. At one location of the concentrated heat source tests were run at a constant power output with 5 different supply air flow rates. The supply air temperature was kept constant through all tests. This gives a wide range of tests with Reynolds numbers between 3600-9200 and Archimedes numbers between 0.007-0.34.

The investigations were performed under steady state air flow and temperature conditions and the conditions were verified by regular measurements of the temperature in fixed points and by regular measurements of the heat supply and the supply air flow rate.

The investigations intended to study the effect of the following parameters on the jet pathway and the air flow pattern in the model:

- Archimedes number
- Type of heat source
- Location of heat source

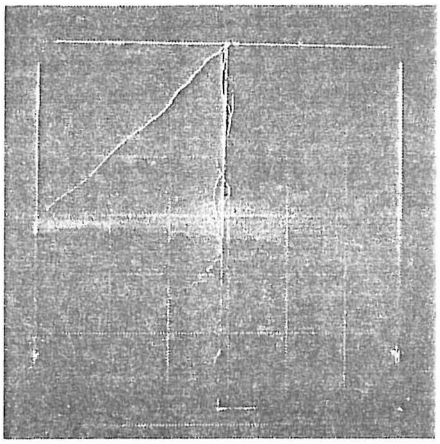
EXPERIMENTAL RESULTS

The investigations of the pathways of the air jets and of the air flow pattern in the enclosure were based on smoke visualizations. The smoke tests were photographed and recorded on video. The tests selected to be presented in this paper are a representative part of the tests performed. The experimental results are presented in the paper as photograps of smoke tests and as figures drawn on the basis of photographs and video recordings.

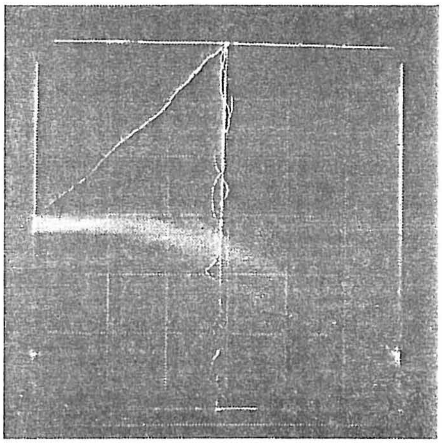
Pathway of supply air jet

Figure 1 shows how the air jet pathway in an enclosure with a distributed heat source covering the whole floor depends on the Archimedes number. The results are compared with the predicted pathways by equation (2). The results of the smoke visualizations show that the supply air jet pathway depends on the Archimedes number and that there is a good correspondence between the visualizations and the predictions. Therefore the presence of the distributed heat source seems not to influence the pathway of the supply air jet.

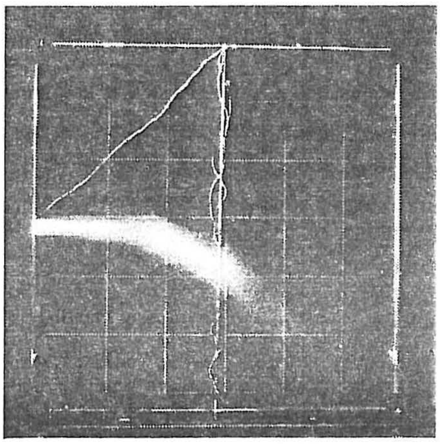
Figure 2 shows how the air jet pathway in an enclosure with a concentrated heat source depends on the Archimedes number. The heat source was located in the centre plane of the enclosure at a distance of $x = 0.56$ m from the wall with the supply opening. The results of these smoke visualizations also show that the supply air jet pathway depends on the Archimedes number but the correspondence between the visualizations and the predictions is not very good. The air jet does not fall as rapidly as in the case with the distributed heat source. In this case the presence of the concentrated heat source seems to influence the pathway of the supply air jet.



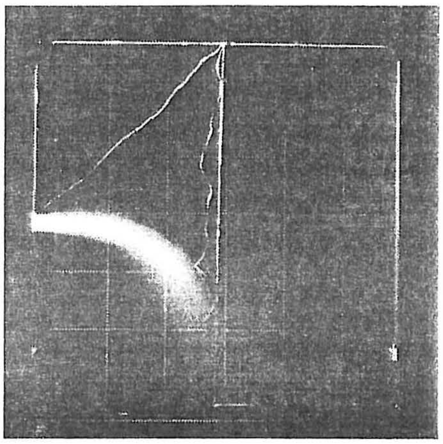
a: Ar = 0.007



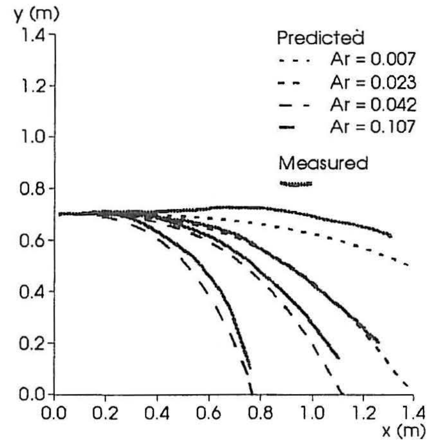
b: Ar = 0.023



c: Ar = 0.042

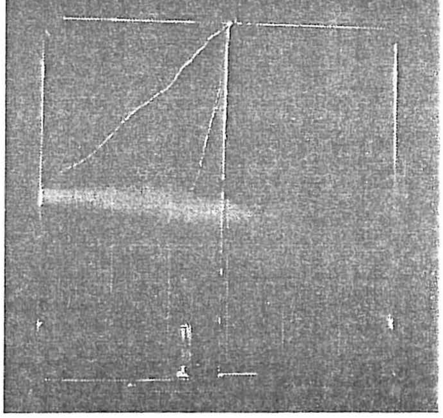


d: Ar = 0.107

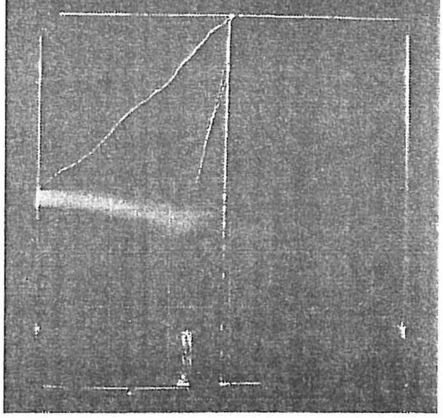


e: Comparison of measured and predicted pathway of supply air jet.

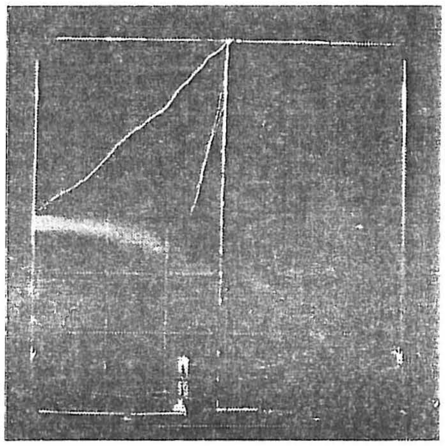
Figure 1. Jet pathway dependence on the Archimedes number with a distributed heat source, type a, in the enclosure.



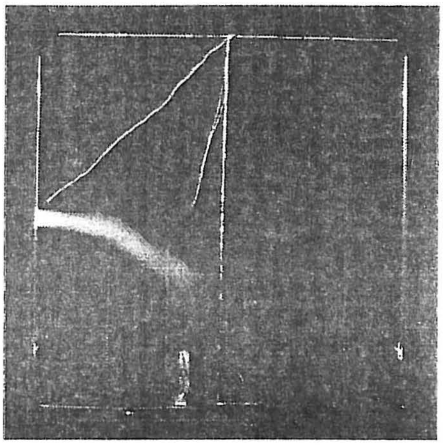
a: Ar = 0.026



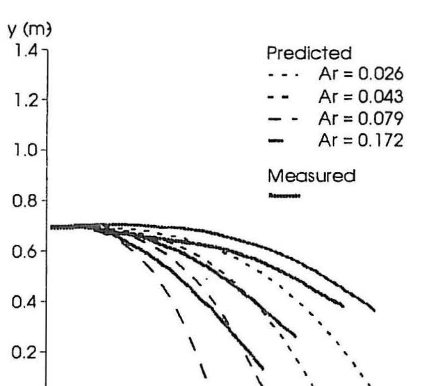
b: Ar = 0.043



c: Ar = 0.079

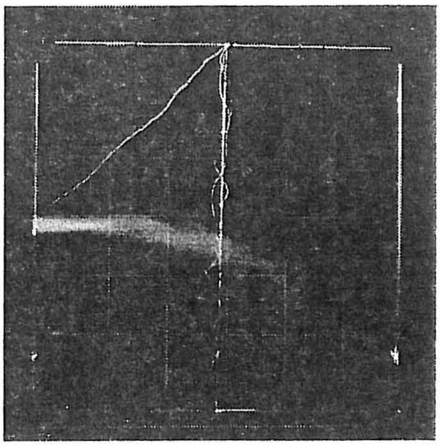


d: Ar = 0.172

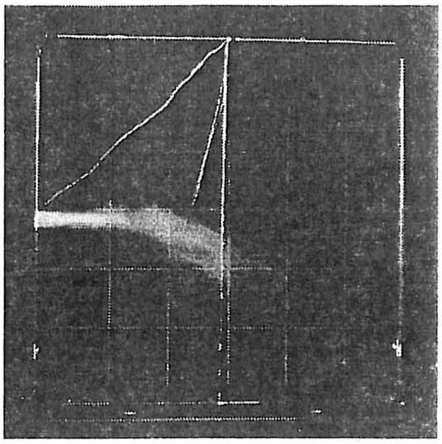


e: Comparison of measured and predicted pathway of supply air jet.

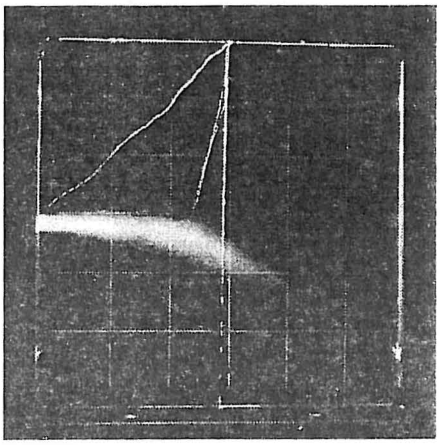
Figure 2. Jet pathway dependence on the Archimedes number with a concentrated heat source, type d, located in the centre plane of the enclosure at a distance of x = 0.56 m from the wall with the supply opening.



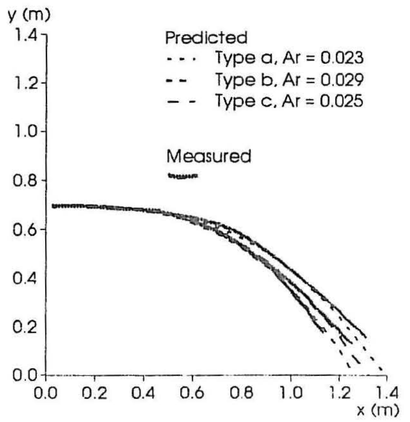
a: Heat source type a, Ar = 0.023



b: Heat source type b, Ar = 0.029



c: Heat source type c, Ar = 0.025

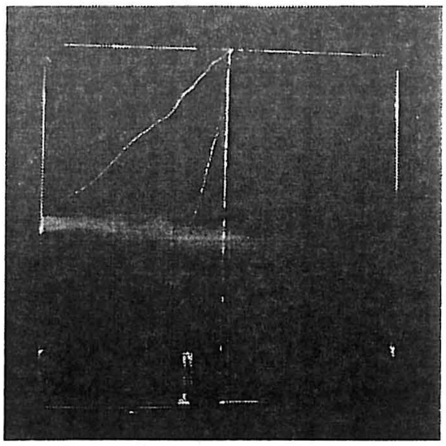


d: Comparison of measured and predicted pathway of supply air jet.

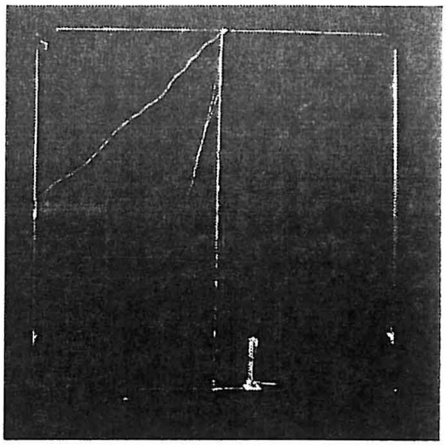
Figure 3. Jet pathway for different types and locations of distributed heat sources at the (almost) same Archimedes number.

Figure 3 shows how the air jet pathway in an enclosure at the same Archimedes number depends on the type and the location of the distributed heat source. When the differences in the Archimedes number are taken into consideration the results show that the type and the location of the distributed heat source do not influence the pathway of the supply air jet.

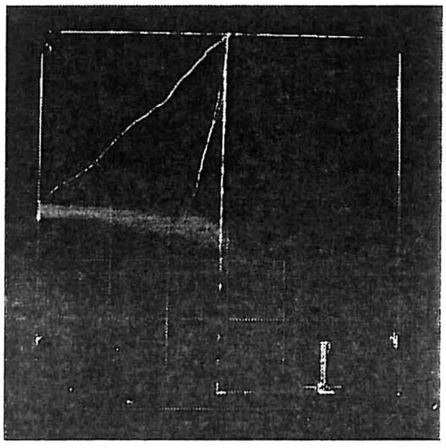
In an enclosure with a concentrated heat source figure 4 shows how the air jet pathway at the same Archimedes number depends on the location of the heat source. Although there is a small difference in the Archimedes number, figure 4 shows that the presence of the concentrated heat source in all three locations influences the pathway of the supply air jet. The largest difference between the measured and the predicted pathway is found for the concentrated heat source located close to the wall with the supply opening and the opposite situation is found for the concentrated heat source located far from the wall with the supply opening. However, the differences between the air jet pathways are very small and they might be caused by measurement uncertainties.



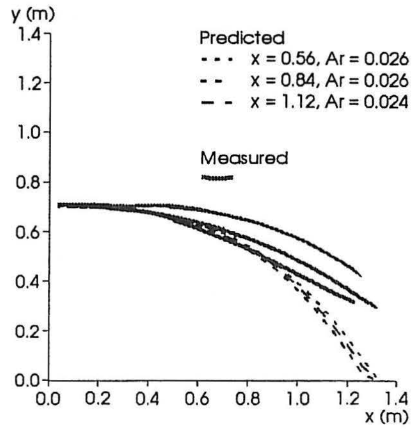
a: Location x = 0.56 m, Ar = 0.026



b: Location x = 0.84 m, Ar = 0.024



c: Location x = 1.12 m, Ar = 0.026

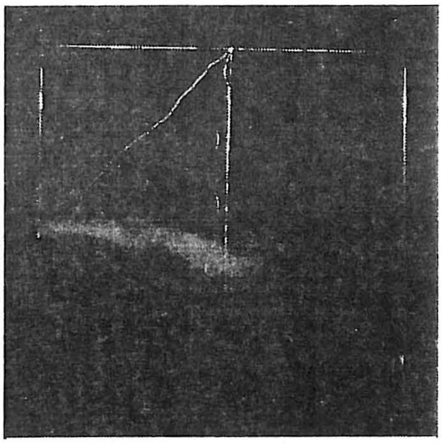


d: Comparison of measured and predicted pathway of supply air jet.

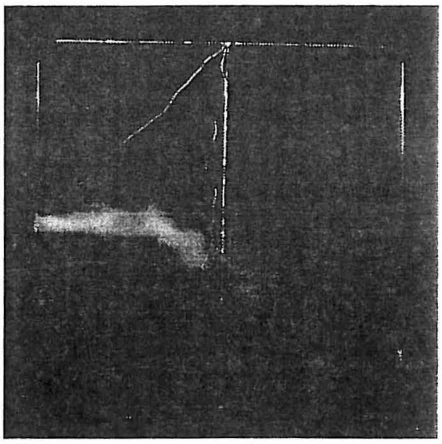
Figure 4. Jet pathway for different locations of a concentrated heat source in the centre plane of the enclosure at the (almost) same Archimedes number.

Air flow pattern in the enclosure

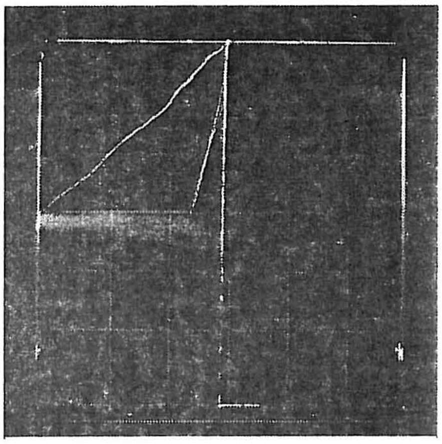
Figure 5 shows with a distributed heat source in the enclosure how the air flow pattern depends on the type of the heat source and on the Archimedes number. The air flow pattern at a low Archimedes number is almost the same for all types of heat sources. The supply air jet reaches the opposite end wall at floor level. There is a return flow in the lower part of the enclosure and a flow of slightly heated air is moving towards the exhaust along the wall with the supply opening. Most of the upper part of the enclosure is not well ventilated.
At a higher Archimedes number the air flow pattern in the enclosure depends on the type of heat source. As it was seen in figure 3 the pathway of the supply air jet is almost the same for the different types of heat sources and it reaches the floor in the enclosure at about 3/4 of room length from the supply opening and divides into two parts. In the test case with heat source type a, one part returns along the floor and continues upward along the wall with the supply opening to the exhaust. Another part continues along the floor and a recirkulation



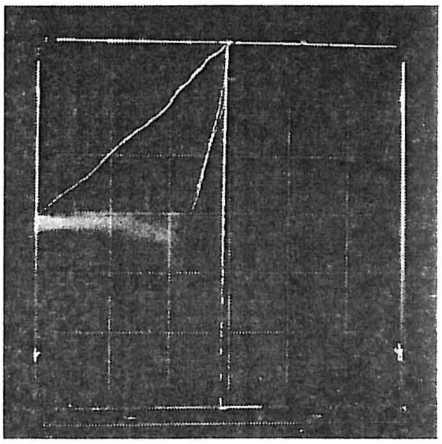
a: Heat source type a, Ar = 0.033



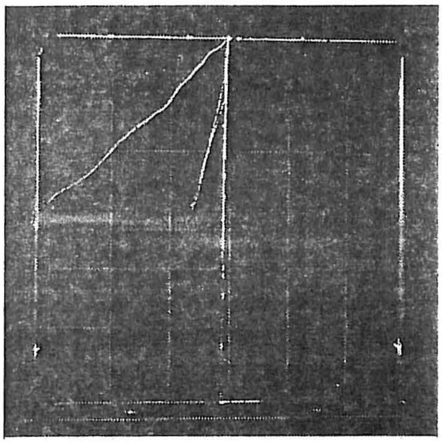
b: Heat source type a, Ar = 0.061



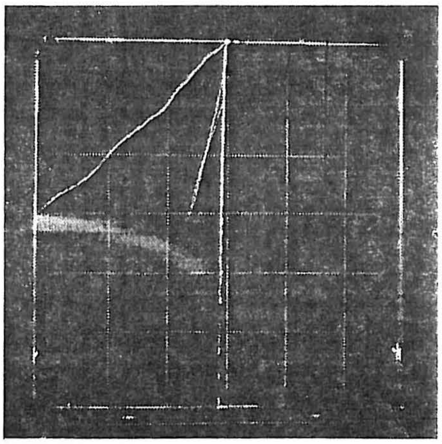
c: Heat source type b, Ar = 0.030



d: Heat source type b, Ar = 0.066

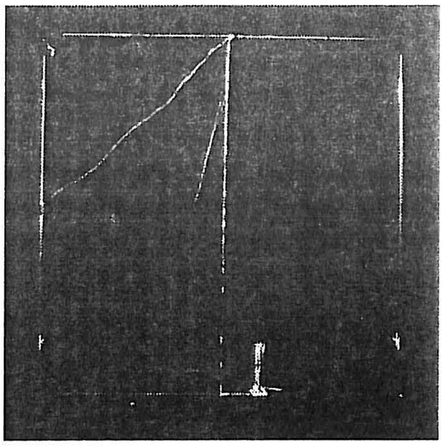


e: Heat source type c, Ar = 0.028

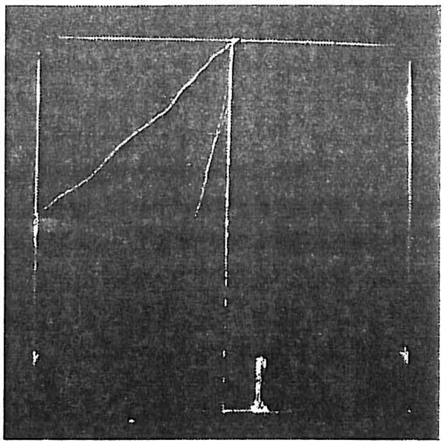


f: Heat source type c, Ar = 0.067

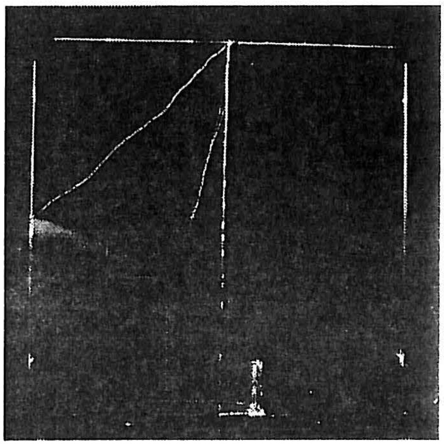
Figure 5. Air flow pattern dependence on the heat source type and the Archimedes number with distributed heat sources in the enclosure.



a: Ar = 0.026



b: Ar = 0.082



c: Ar = 0.341

Figure 6. Air flow pattern dependence on the Archimedes number with a concentrated heat source, type d, located in the centre plane of the enclosure at a distance of x = 0.84 m from the wall with the supply opening.

zone is formed between the jet and the opposite wall. In the test case with heat source type b a much larger part returns along the heated part of the floor and upward along the wall and only a small part continues along the unheated part of the floor. In the test case with heat source type c the situation is in principle the same. Here almost all the air continues along the heated part of the floor and upward along the wall opposite the supply opening and only a small part is recirculated.

In an enclosure with a concentrated heat source figure 6 shows how the air flow pattern depends on the Archimedes number. The heat source was located in the centre plane of the enclosure at a distance of x = 0.84 m from the wall with the supply opening. At a low Archimedes number the supply air jet reaches the opposite end wall at floor level and the air flow pattern in the enclosure looks the same as for the distributed heat source at a low Archimedes number. At a higher Archimedes number the supply air jet reaches the floor at the location of the heat source about 2/3 of room length from the supply opening. The air flow continues along the floor and upward along the wall opposite the supply opening as it was seen in the test case with heat source type c. In both situations the convective flow from the heat source is suppressed by the recirculating flow and the supply air jet, respectively. In the test case with a large Archimedes number the supply air jet reaches the floor at about 1/2 of room length from the supply opening and divides into two parts. One part returns along the floor and a recirculation zone is formed below the supply. Another part continues along the floor and a recirculation zone is formed between the jet and the opposite wall. In this case the air flow along the floor is not able to suppress the convective flow from the heat source. A convective plume is formed above the heat source which transports air from the lower part of the enclosure to the ceiling.

DISCUSSION

The tests showed that the pathway of the supply air jet depends on the Archimedes number. A distributed heat source e.g. a heated floor or a heated part of the floor had no influence on the pathway of the jet and the results showed a good correspondence with the predicted pathways found in e.g. equation (2).

A concentrated heat source in the enclosure changed the pathway of the supply air jet so it did not fall as rapidly as in the case of the distributed heat source. The vertical temperature distribution in the enclosure was measured in two different locations outside the pathway of the supply air jet. The measurements showed both in the case of the distributed heat source and in the case of the concentrated heat source approximately the same temperature gradient in the enclosure. A smaller temperature difference between the supply air jet and its surroundings as mentioned by Murakami, [2], was therefore not the reason for the difference in jet pathway. It was seen on the video recordings that the supply air jet almost entrained all the warm air in the convective plume above the heat source. This gives higher temperatures in the supply air jet and the jet will therefore not fall as rapidly as expected. However, detailed measurements of the temperature distribution in the jet are needed before this explanation can be verified.

For flow conditions at a low Archimedes number the experiments showed that the air flow pattern in the enclosure was determined by the supply air jet. For flow conditions at a higher Archimedes number where the strength of the jet becomes relatively smaller the pathway of the jet was still independent of the type and location of the heat source, but the experiments showed that the air flow pattern in the enclosure more and more was determined by the convective flow from the heat source. This means that the thermal comfort and the risk of draught in the occupied zone, because of low temperatures and high velocities in the supply air jet, are possible to estimate from the traditional jet theory while the atmospheric comfort and the ventilation efficiency in the occupied zone also depend on the type, location and strength of the heat sources.

CONCLUSION

The model experiments show that the penetration depths and the paths of cold jets in enclosures were not influenced by the presence of distributed heat sources e.g. a heated floor and only slightly influenced by the presence of concentrated heat sources. However, different locations and different strengths of the heat sources resulted in quite different air flow patterns.

In the design procedure of ventilation systems it is therefore possible to estimate the thermal comfort and the risk of draught in the occupied zone because of low temperatures and high velocities in the supply air jet from the traditional jet theory, while the influence of heat sources on the air flow pattern is needed for the estimation of the atmospheric comfort and the ventilation efficiency.

ACKNOWLEDGEMENT

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NOMENCLATURE

A_o	= Air Supply Area	(m^2)
c_p	= Specific heat	(J/kg °C)
g	= Gravitational acceleration	(m/s^2)
k_1	= Constant	
k_2'	= Constant	
l	= Characteristic length	(m)
Δt_o	= Temperature difference between exhaust and supply	(°C)
u_o	= Inlet air velocity	(m/s)
x	= Horizontal distance	(m)
y	= Drop from initial centre line	(m)
β	= Thermal expansion coefficient	($°C^{-1}$)
λ	= Thermal conductivity	(W/m °C)
μ	= Dynamic viscosity	(kg/m s)
ν	= Kinematic viscosity	(m^2/s)
ψ	= Constant	

Ar_o = Archimedes number, $Ar_o = (g\ \beta\ \Delta t\ \sqrt{A_o})/u_o^2$
Pr = Prandtl number, $Pr = (\mu\ c_p)/\lambda$
Ra = Rayleighs number, $Ra = (g\ \beta\ \Delta t\ l^3\ Pr)/\nu^2$
Re = Reynolds number, $Re = (u_o\ \sqrt{A_o})/\nu$

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