EFFECTIVE VENTILATION

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Paper 3

EXPERIMENTAL ANALYSIS OF AIR DIFFUSION IN LARGE SPACE

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Synopsis

An experimental study in reduced scale model for ventilation inside a sheep-fold has been studied. The ventilating system consist of two slots in opposite side walls and one in the roof. Two-dimensional jet are generated by the wind effect and temperature difference acting upon the sheep-fold. The jets generate several low pressure zones in the sheep-fold and these zones in term produce the deflection to the jet flow. The position of these zones in the space change dramatically even with a little variation of the thermal and dynamic boundary condition and therefore the movement of air in the space change due to this unstable phenomenon.

The flow pattern, have been studied in function of different parameters such as Archimedes number, Reynolds number, flow rate for every inlet, velocity profile and turbulence in the inlet, situation of exhaust and length of the air inlet (slot) in relation to length of the wall.

It has been found that the main factors governing the air circulation are: relationships between the flow rates of the two inlets, relationship between the length of the slot and the length of the wall and the Archimedes number. However the mean velocity in the occupation zone is not very much affected by the above factors.

In conclusion we estimate that this ventilation system by considering its low cost is suitable for this kinds of application. However, disadvantage may occur when a low pressure zone is formed between the inlet and the roof which could result a short-circuit in air flow.

List of symbols

Ar : Archimedes number.
B : Length of the slot. [m]
H : Length of the wall. [m]
Lr : Distance of jet attachment point from the wall [m]
N : Number of nodes used to describe the studied zone
R : Radius of curvature of the jet
Re : Reynolds number
Re c : Critical Reynolds number
SD : Dimensionless space standard deviation of mean velocity
Ui : Mean velocity in each point in the occupation zone [m/s]
Um : Dimensionless mean velocity in the ocupation zone
Uma : Dimensionless maximum velocity in the occupation zone
U0 : Velocity at the inlet [m/s]

1.- Introduction

In recent years, it is becoming more and more important to achieve good performance in all economic aspects; among others, animal production is in one of these race. The purpose of the agriculture climatisation of animal production is to control certain parameters of the internal environment , so as to maintain the animals healthy . These parameters are generally: concentration of different gasious contaminent, humidity, velocity and temperature of air.

For this purpose it is interesting to increase the understanding of air movement in a large enclosure by means of the simplist ventilation system, i.e. two dimensional jets from a slot at the side walls . This system arrangement can also be useful for industrial applications.

In this paper the results of an experimental work in a reduced scale model of sheep fold are presented in which the air flow pattern and velocity field for different parameters such as :Achimedes number, Reynolds number , velocity profiles and turbulence at the inlet, relationships between flow rate for each inlet and other parameters for the identification of micro-climate are studied.

It has been found in this study that the temperature difference between the inside and outside is small due to the low heating load in the building and therefore, the wind effect acting upon this building becomes very important.

2.- Building and model description:

The real sheep-fold in Sart-Tilman, Liege is taken for this study. This construction is 20 meters long, occupied by 200 sheep with heat emission rate approximately 60 W each. In this paper only the heat emission from animals and uniformately distribued on the floor, is considered. Of course, the position of the heat source also influences the air flow patterns, but this aspect is not taken into account in this paper.

Similarity rules

It is not possible to follow all the non-dimensional numbers derived from the Navier-Stokes equation of fluid mechanics in experiment. For this reason, with practical recommendation from reference [1], [2] and [3] the following similarity rules are applied:

Isothermal test

a) Geometric similarity

b) Re in model = Re in prototype

If Re > Re c the only condition is geometric similarity

Non isothermal test

a) Geometric similarity
b) Ar in model = Ar in prototype
c) Re > Re c

As the main interest is to know the air flow in the enclosure, heat losses through walls has been excluded for this study. Also the concept of local modelling is applied and the study is focused on the internal zone.

The test facility

Figure 1 shows the 1/3 scale model of the real site sheep-fold of Sart-Tilman built for this study in the Laboratory of Thermodynamic, University of Liege. The effect of ventilation, mainly resulted from wind, is produced by 2 ventilators for to keep the same pressure inside and outside of this model so as to minimize the infiltration effect. The heat emission from animals are simulated by heating carpets on the floor of the model.

In this model 3 different air inlet conditions of velocity profile and turbulent intensity can be studied (turbulence intensities are 2%, 5% and 10%). The studies of these air inlet conditions will give knowledge to the further evaluation of the design of air inlets .

3.- Measuring method and measuring equipment

Omnidirectional probe TSI model 1620 has been used for measurements of mean velocity of the air. This probe is a constant temperature anemometer with temperature compensation. The response time is approximately 2 seconds.
The accuracy (over 240° solid angle) is ± 10 % over 0.2 to 3 m/s and +5% to -20% ± 0.04 m/s over 0 to 0.2 m/s. The velocity of free convection from the heated sensor is near of 0.02 m/s.

For the turbulence measurements of the inlet a DISA hot wire anemometre and a RMS voltmeter was used, the frequency bandwidth in this measurement was limited at 90 Hz.

All temperatures were measured with thermocouples type T and voltages with the integrated measurement system Solartron 3510. The Solartron system was controlled, on line, by a micro computer.

By measurement, in different position of the jet, within a long period, the optimal time of measurement

has been calculated and error produced by taking measurements only on short time have been estimated.
For 30 minutes of velocity measurements, 2 seconds each, the mean velocity for every 20 seconds period and the standard deviation between each 20 seconds mean velocity and total mean velocity are calculated. This standard deviation is a kind of measurement of error for taking mean velocity within only 20 seconds rather than a measurement with 30 minutes.
Measurement in different time periods and positions in the jet has been made as show in figure 2, and it can be seen that 4 minutes of measurements period is a good compromise between the accuracy and the time of measurement.

By an automatic positioning system , the anemometer can be placed anywhere in the model and for every test, near of 180 points of measurement of velocity and temperature in one section of the model was taken. Every 30 minutes 70 fixed temperatures on the wall and in the air are checked to ensure the steady-state condition.

The following parameters have been studied in different test: Reynolds number between 1500 to 6000 ; Arquimedes number from -0.004 to 0.03; 1 or 2 inlet of air; exhaust at the roof or on the opposite wall ; slot covering the entire wall (B/H = 1) or not (B/H = 0.83) and 3 velocity profiles and turbulence intensities in the inlet .

4.- Results

Figure 3 shows different parameters describing the geometry used in the following text.

4.1.- Air flow patterns

One air inlet

Figure 4 shows the air flow for test with only one isothermal air inlet with B/H = 0.83. In this case three dimensional flow has been observed near the wall while in the middle of the model the flow is two dimensional. The air jet has slight deflection due to Coanda effect .

Figure 5 shows a similar test condition but with an air inlet in all the length on the side wall (B/H = 1), in this case the deflection of jet becomes significant.
The entrainment of fluid near to the floor cause a low presure zone between the jet and the floor curving the jet toward the floor. When the jet striks the floor, a proportion of the volume flow is re-entered into the low pressure zone to supply the volume of air necessary for the entrainment from the low pressure zone.

Isothermal studies of this phenomenon can be found in references [4] and [5]. Timmons et al. [6] have found that the coanda effect dissapears when the predicted attachment length (Lr in figure 3) is approximately the length between the two walls. In air curtain studies [7], the same kind of deflection of jet, due to low pressure zone, has been found.
In the test of figure 4 a proportion of the air re-entered into the jet is from other part of the building and so the deflection is not so important.
In non-isothermal condition there is more significant effect on deflection of the jet but the circulation of air does not change very much.

Two air inlets and B/H = 1

Figure 6 is with high Archimedes number and the two jets are reattached to the floor due to Coanda and Ar effects.

Figure 7 shows a test for very low Ar number (close to 0). In this case the flow pattern is very different from the previous. There is only one jet reattached to the floor and another attached to the roof. Since in tests with only one jet, it always attaches to the floor, this means that the interaction between the jets may change the flow patterns of the air completely.

Figure 8 and 9 shows the same test with similar Re and Ar conditions at both inlets and at moderate Ar. During the first 7 hours of the test (figure 8) the air flow pattern is similar to case of figure 6. After 7 hours of test, the air flow pattern changes completely and there is still one jet attached to the floor but another goes over the first one. It flows upward approching the roof but there is no attachment to the roof, because in this case the air density of the top jet is greater than the air of the room

This is an example of the instability of the two dimensional flow where the flow patterns may changed by little disturbance. It is important to consider that the intensity and direction of wind are changing all the time and so different flow patterns may appear in a short period.
It is possible to take every situation as a steady state problem and use an statistic method to find the mean flow condition.

4.2 Deflection of the jet in the room

The centre line of a jet can be well represented by an arc of circle and therefore the position of the jet can be determined by the radius of curvature. Figure 3 shows this. For present result, it is possible to find the equation of central line by calculating the maximum velocity for different vertical velocity profile.

Figure 10 shows the radius of the curvature R as function of Re for ¦Ar¦<0.001. It can be found that there is no clear dependence of Re for Re>2000. With linear regression analysis the slope has been found as: 1.8E-5 ± 5.8E-5 . This means that the random errors are greater than the influence of Re. With this result and results of other work, it may be concluded that for Re>2200 the position of the jet is independent of Re. Other researchs [1] show also that when we found a critical Re for a reduced model, it can also applied to the prototype .

Figure 11 shows the radius of curvature as function of Ar for tests with only one air inlet, Re >2200, B/H= 0.83 and B/H = 1 (The results concerning B/H = 1 are extracted from figure 12) .
For test with B/H = 0.83 radius R decreases significantly when Ar inceases and the effect becomes more sensible at low Ar.
For test with B/H = 1, Ar affect the jet only later 0.004 and this influence is little. The influence of B/H near of Ar zero is significant due to variation of Coanda effect, but for Ar sufficiently large B/H has no importance.

Figure 12 shows results of R as function of Ar for Re > 2200 and B/H = 1 and for a number of test with one or two inlet. In case where one inlet was used three different velocity and turbulence air inlet conditions and also exhaust at the roof or at another wall, were considered. The influence of this parameters on the jet deflection is not significant. When 2 inlets are used, only one jet was attached to the floor (only test with moderate Ar are considering)and in this case R is slighty higher. Therefore it can be expected that with two inlet of air the deflection of the jet flow attaching to the floor would be smaller than those with one air inlet.

4.3 Velocity in the occupation zone

Whit about 150 measurement point in the zone A of figure 1 and by linear interpolation between these point we obtained the full mean velocity profile in this zone. With these values the mean velocity field for the occupation zone (defined in figure 1) are going to be analyzed by the following parameters.

Um : Mean velocity in the occupation zone

$$Um = \Sigma U'i/N$$

where $U'i = Ui/U0$

SD : spatial standard deviation of mean velocity. Give an idea of the homogeneity of the velocity in the occupation zone.

$$SD= \sqrt{(\Sigma(U'i-Ui)^2/N)}$$

Uma : Maximum mean velocity in the occupation zone

Figure 13 shows the relationship between the mean velocity in the occupation zone and R for B/H = 0.83, and one inlet. It has been found that Um decreases linearly in relation with R with a slope of -1.6 ± 0.07.

For test with B/H=1 as shown in figure 14, the same tendency has occurred but the results are more scattered. In fact in this case the variation of R is small and the jet arrives, in each case, very quickly into the occupation zone.
The possibilities of different inlet condition, positions of the outlet and numbers of inlets are included in this figure; however due to high scattering of data ,it is not possible to determine the special influence of each of these parameters with relation to the mean velocity of the occupation zone.
It is necessary to note that there is not much difference between tests with one or two inlet.

In the point of view of homogeneity of mean velocity field in the occupation zone, figure 15 and 16 show that the SD increases when R decreases. But for B/H = 1 it can be seen that the scattering of results is also very high.

Figures 17 and 18 show that maximum velocity (Uma) increases when R decreases and in this case the scattering of data is lower.

In general the velocity distributions in the occupation zone are not a Gaussian function shaped and therefore it is necessary to study such distribution by histogram. Figures 19, 20, 21 and 22 are examples showing the percentage distribution of the mean velocity for different radius of curvature of the jet. It can be seen that for high R values, 2 peaks exist, one in the low velocity zone and another in the high velocity zone (jet zone) .In this case jet has grown sufficiently before reaching the occupation zone with a large volume and moderate velocity. When R decreases, the jet reaching the occupation zone is less developed, but at higher velocity, and this makes the second peak disappear, because now only a little zone with high velocity has resulted.

Figures 23, 24, 25, and 26 are examples showing the mean velocity field in zone A of the model, it is expressed in tenth of the outlet velocity (U'= 10 * U / U0).
In figure 23 we can see that the jet passes through the space with a low and homogeneous velocity in the occupation zone(the three lines at the bottom of the

figure represent the occupation zone). In figure 24 with R=0.3 the jet passes through the occupation zone at high velocity . Figure 25 is for test with 2 inlets at Archimedes number close to 0, it can be seen that the influence of the second jet in the occupation zone is not high and this results in a velocity field in the occupation zone similar to the test with only one inlet. Figure 26 shows a test with 2 inlets at high Archimedes number .

5.- Discussion and conclusions

Optimal values and estimated error for the time of integration of the velocity measurement has been found experimentally. These values agree in general with analysis of autocorrelation [8], but a detailed comparison is not possible due to low frequency of velocity measurements.

In general, due to two dimensional characteristic of the flow, there is a formation of low pressure zones . Whether exist or not of these zones makes the air movement in the model change completely without sensitive changes of other conditions. It produces a unstable flow; Timmons (4) found also bistable flows for some geometries in a similar problem.
The instability problem and the fact of different time constants for the air and walls result that temperatures in walls are not directly in relation with instantaneous flow and it depends on mean flow pattern in long time.

The changing external condition (wind), results in various highly different internal air movement and it is very difficult to estimate the actual flow condition in the real building . Considering heat load conditions, wind velocity and heat capacity of walls and ground, the air movement in the inside can be considered as a mean weighted value of the following particular situations: one air inlet and the jet deflected to the occupation zone; two air inlet with one jet deflected to the occupation zone and another deflected towards the roof and two air inlet in which both jets are deflected to the occupation zone. The exact position of the jet depends mainly of Archimedes number.

No much differences in mean velocity of the occupation zone have been found for different air flow patterns studied where at least one jet is deflected to the occupation zone but the mean velocity becomes smaller if $B/H \approx 1$ and Ar closed to zero.

All situations studied above, give good mean velocity in the occupation zone, for sheep need; only when R is very small some high velocity may occur in a very little zone in the space.

In the most cases, except for quite different flow rates in two inlets and at low Ar, the jet came directly into the occupation zone and we have a very good ventilation efficiency.

To decrease the length of inlet in relation to length of the wall at Archimedes number close to zero, plays a role unfavorable to the point of view of ventilation , this effect would become less and less when Ar increases. It is beneficial to have this effect if we can sacrifice a little the ventilate efficiency to decrease the mean velocity in the occupation zone.

It has been found that the velocity profile and turbulence intensity at inlet (given by the design of this one) have very little influence for the determination of the internal micro-climate in this kind of ventilation system.
It has also been verified that the position of air exhaust does not affect much the flow conditions in the occupation zone but is possible to have a "short-circuit" of fresh air which flow directly from the inlet to the exhaust in the roof when a low pressure zone is present between the jet and the roof.

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"Heat transfer characteristics of the air curtain ", ASHRAE Trans. 75 part 2 , 1969, pp 153-167.
8.- TENNEKES, H. and LUMLEY, J. L.
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FIGURE 1 REDUCED SCALE MODEL OF A SHEEP-FOLD

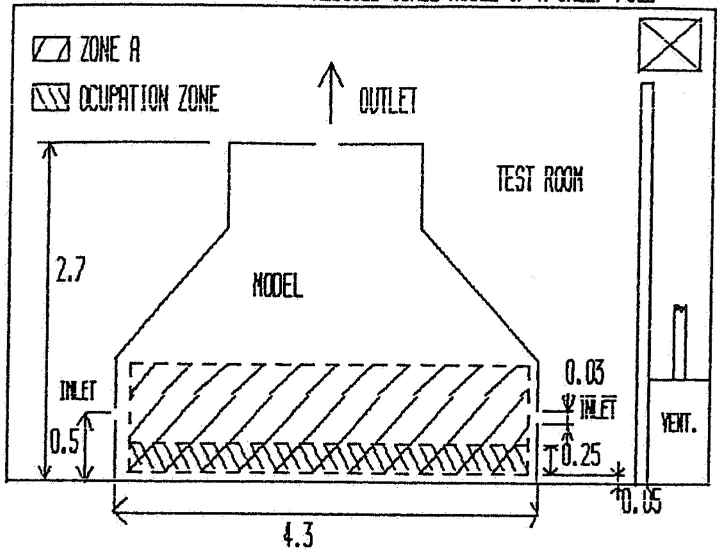


FIGURE 2

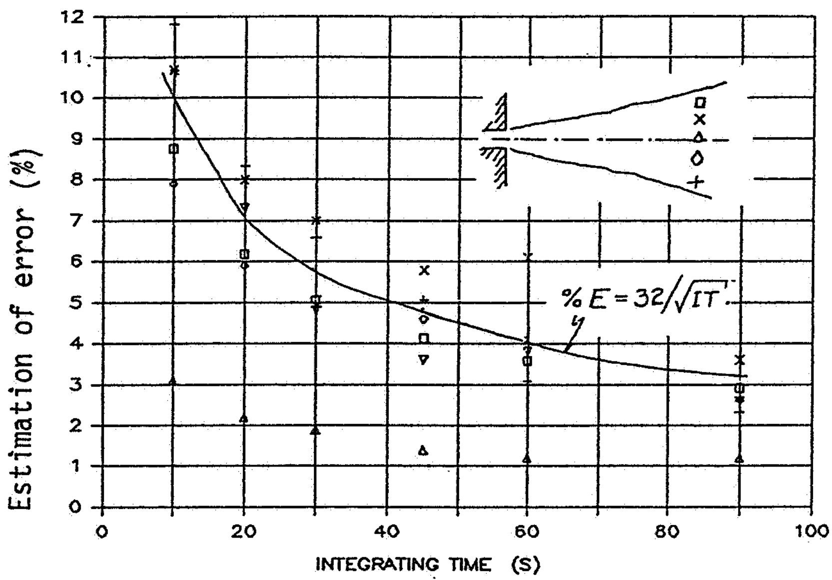
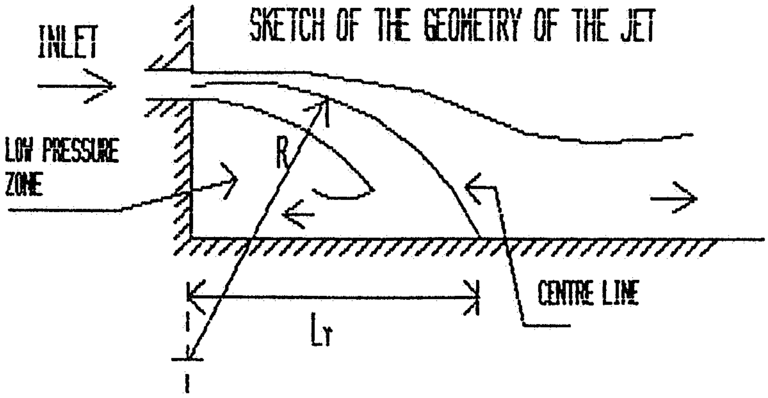


FIGURE 3.
SKETCH OF THE GEOMETRY OF THE JET



AIR FLOW PATTERNS

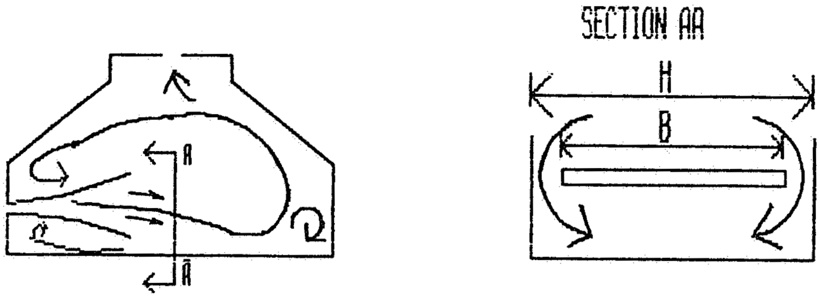


FIGURE 4. $Ar = 0$ $B/H = 0$

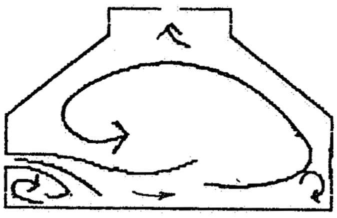


FIGURE 5

$Ar = 0$ $B/H = 1$

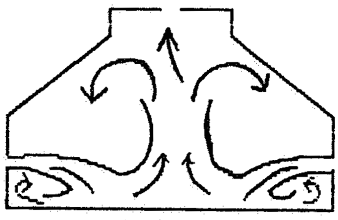


FIGURE 6.

$Ar1=0.019$ $Ar2=0.023$

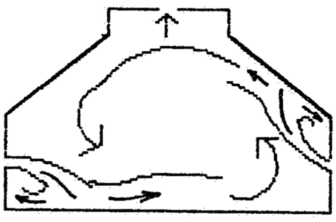


FIGURE 7.

$Ar=0$ $Re1=1700$ $Re2=2400$

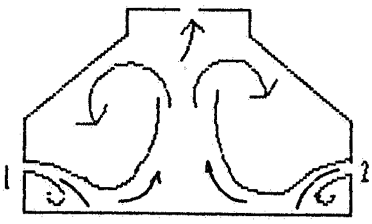


FIGURE 8.

FIRST 7 HOURS

$Re1=2500$ $Re2=2600$

$Ar1=0.005$ $Ar2=0.005$

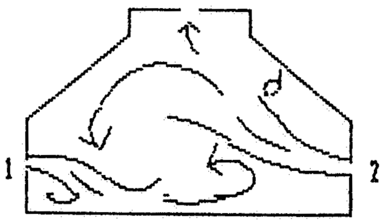


FIGURE 9.

AFTER 7 HOURS

FIGURE 10
R = f (Re)

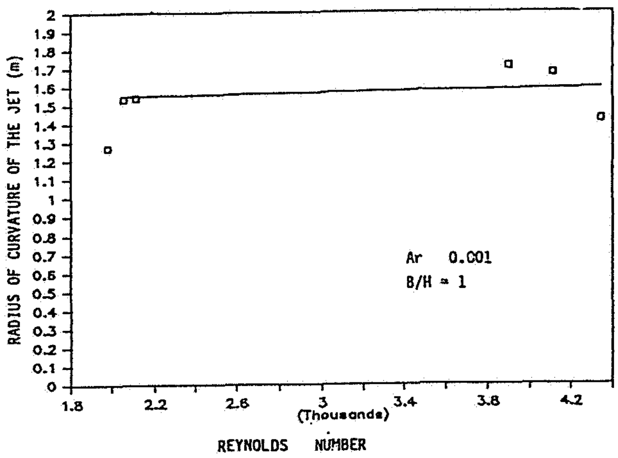


FIGURE 11
R = f (Ar) for one air inlet

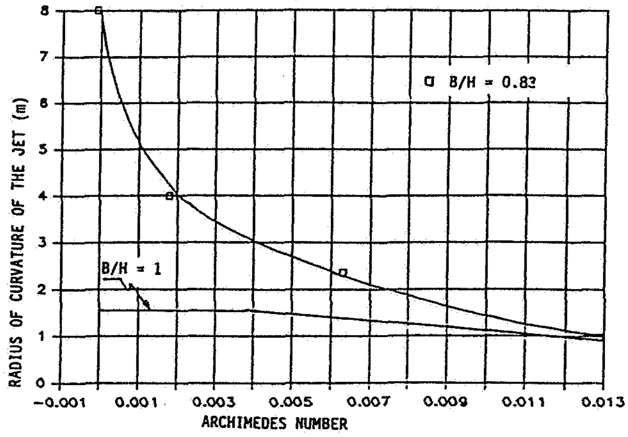


FIGURE 12
R = f (Ar) for B/H= 1

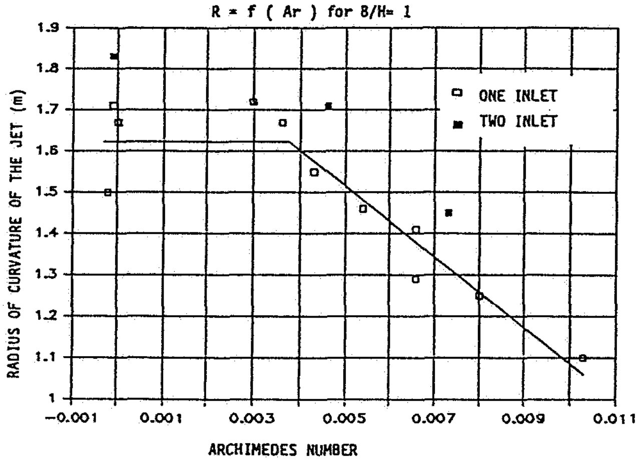


FIGURE 13
Um = f (R) for B/H = 0.83

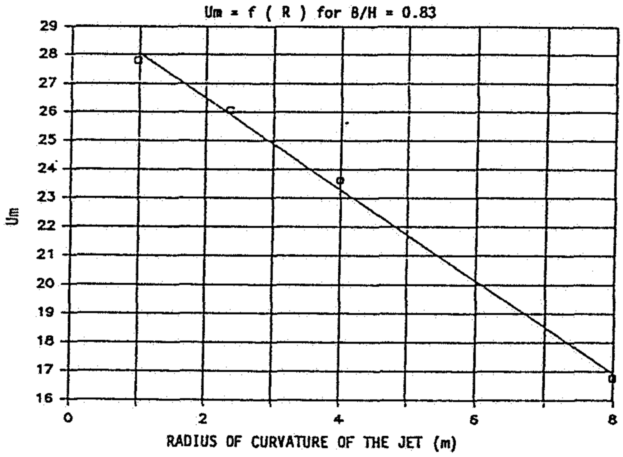


FIGURE 14
Um = f (R) for B/H = 0.83

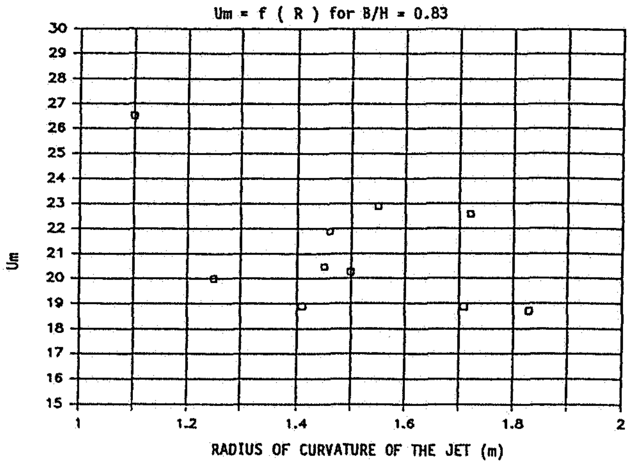


FIGURE 15
SD = f (R) for B/H = 0.83

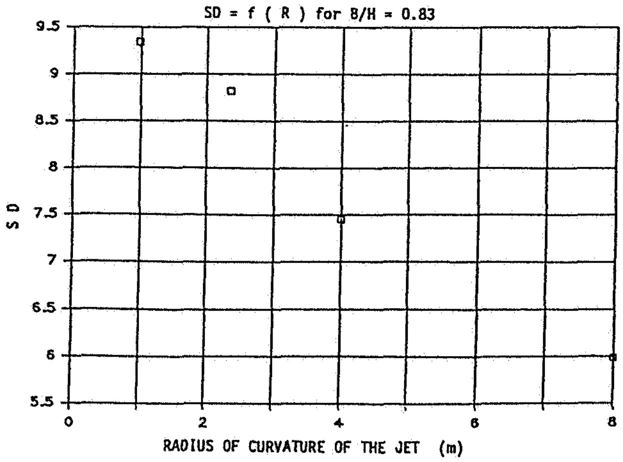


FIGURE 16

SD = f (R) for B/H = 1

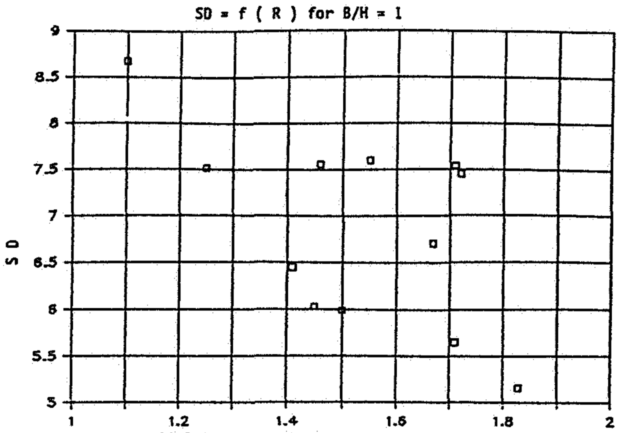


FIGURE 17

Uma = f (R) for B/H = 0.83

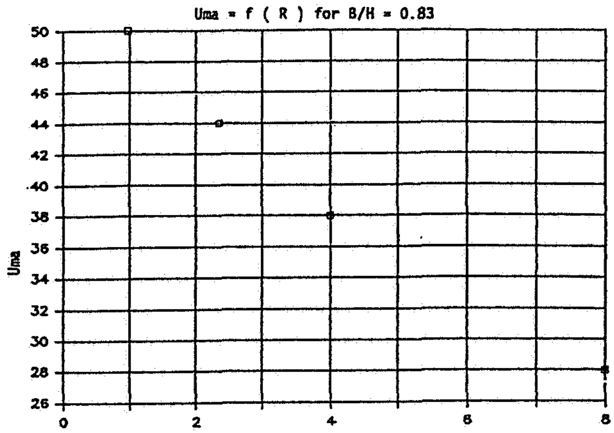


FIGURE 18

Uma = f (R) for B/H = 1

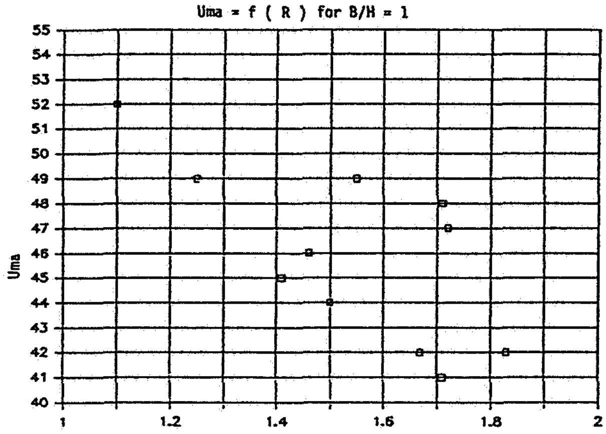


FIGURE 19

HISTOGRAM FOR R=8

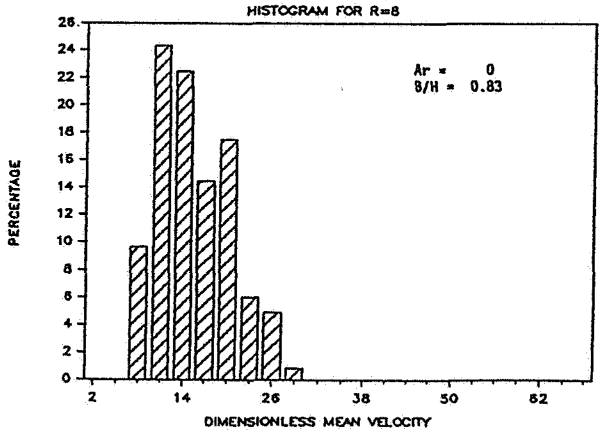


FIGURE 20

HISTOGRAM FOR R=1.9

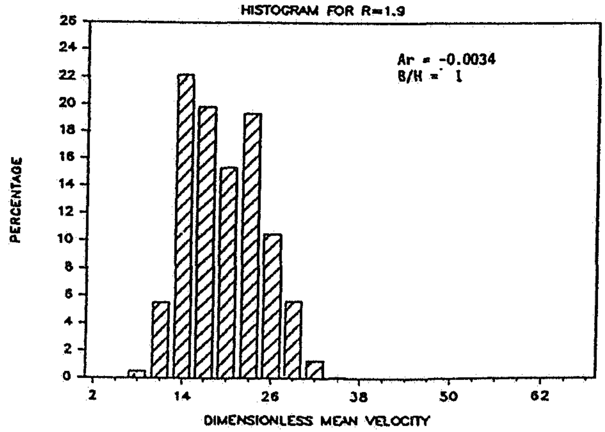


FIGURE 21

HISTOGRAM FOR R=1.46

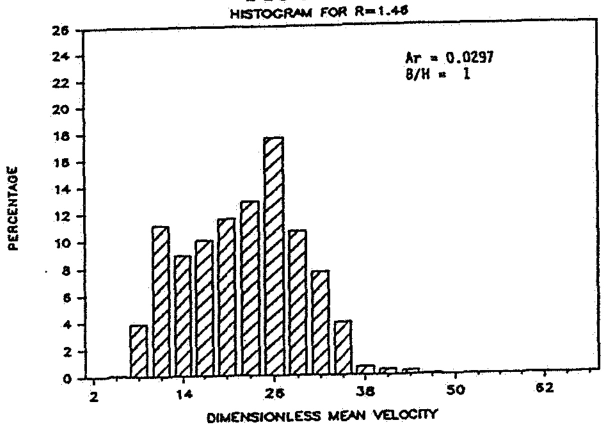


FIGURE 22

HISTOGRAM FOR R=0.3

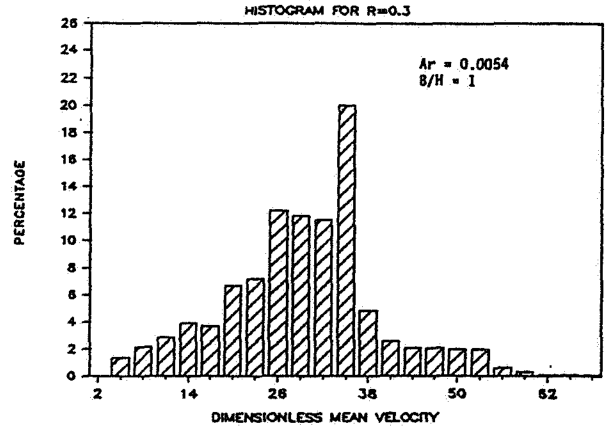


FIGURE 23

MEAN VELOCITY FIELD

B/H=0.86
R = 8
Ar = 0

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111111111111111111111111111111111111111111111111111111111111111111111111100000000000
11111111111111111111111111111111122111111111111111111111111111111111111111111110000
111222221111111111111111111111112222222221111111111111111111111111111111111111111111
222222222221111111111111111122222222222211111111111111111111222111111111111111111111
111111111111111111111111111112222222222222222222222222222222222222222211111011
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111111111111111111111111111111122222222222222222222222222222112211111111111111111111
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FIGURE 24

MEAN VELOCITY FIELD

B/H=1
Ar=0.0297
R = 0.31

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1111111111111111111111111111111111111111111100000000000001111111111000000000000000000000
111111111111111111111111111111111111111111110000000000000111111111000000000000000000000
111111111111111111111111111111111111111100000000000000000000000000000000000000000000000
1111111111111111111111111111100001111111111111111111111110000000000000000000000000001131
1111111111111111111111111111000001111111111111111111111111100000000000000000000000011161
111111111111111111111111100000000000111111111111111111111111111000000000000000000000000011199 ←
2222221111111111111111111111111111111111111111111111111111111111111111100000113599 61
222222222222222222211111111111111111112222222211111111111111111111111111001123795111
222222222222222222222222222222222222222222233333222222222222222221111111111111247743111
33333333333333333333333333333333333333333333333333333333333333332222211112457421111
222333333333333333333333333333333333333333333333333344444444444444444333334564 22111
222222233333333333333333333333333333333333333333344444445555555555555554444333222
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FIGURE 25

MEAN VELOCITY FIELD

B/H = 1
Ar = 0

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11111111111111111000000000000000000000000001111111111111111111111111112222222222221111111
11111111111111111000000000000000000000011111111111111111111111111111112222222222211111111
000000000000000000000000000011111111111111111111111111111111111111111222222322211111111
111111111111111111000001111111111111111111111111111111111111111111111111222222233332211111
1111111111111111111111111111111111111111111111111111111111111111111122222233343332 11
→ 9965544332211111111111111111111111111111111111111111111111111111111111111222223334455 6 ←
1376655543333221111111111111111111111111111111111111111111111111111111111222222233 11
1111233433444332211111111111111111111111111111111112222222211111111111111111111122221111
1111112223343332222222111111222222222222222222222222222222211111111111111111111111111
1111111222222222222222222222222222222222222222222222222222111111111111111111111111111
11111111112222222222222222222222222222222222222222222222221111111111111111111111111111
111111222222222222222222333333333333333333333333332222222222222111111111111111111112111111
```

FIGURE 26

MEAN VELOCITY FIELD

B/H = 1
Ar1=0.019
Ar2=0.023

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111111111111111111111111111111111111112222222222221111111111111000000000111111111111111
111111111111111111111111111111111111122232222222111111111111111000000000111110001111111 1
111111111111111111111111111111111111122333222222111111111111110000000000111110000011111 0
111111111111111111111111111111111111112233332222111111111111111111111111111111111111111000
1111121111111111111111111111111111111122333322221111111111111111111111111111111111111111111
→ 8776543222111111111111111111111111111122333332211111111100011111111111111111112222345789 99 ←
11266555432222111111111111111111111111122233322221111111111111111111111111122334556774111
112234554443322211111111111111111111122233332222222111111111111111111111222345554332222 2
11112234444443332222111111111111112222223333333222222222222222111222222222223454322222111
1111222334444333332222222222222222222222333333333333333322222222222222222223333322211111 1
2222222222334333333333333333333333333222222333333333333333333333333323333332221122222 2
33333333333333333344444444444443333333222222223333333444444444444433333333323333332222
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Discussion

Paper 3

J. Van Der Maas (Ecole Polytechnique Federale de Lausanne, Switzerland). (a) What is the dimension on which Reynolds and Archimedes numbers are based? (b) With reference to Figures 8 and 9: is the time scale (7 hours) of any importance and can you confirm that it was not known what parameter changed (after 7 hours)? (c) During the smoke visualisation were the air flow patterns disturbed by the light (smoke particles might be heated by radiant energy from the light source)?

P. Nusgens (University of Liege, Belgium) (a) Height of inlet. (b) The 7 hour time scale was not important and we could not identify what parameter changed to produce the change in airflow patterns. (c) Care was taken to work at low light levels and to measure velocities before and after visualisation; the instability was not observed to be influenced by the radiant heat from the light source.

M. Liddament (AIVC, Warwick Science Park, UK) In mild climates natural ventilation is very popular. Is it possible to develop this work to produce recommendations for the design of inlets for human habited buildings which would provide adequate ventilation over a wide range of climate conditions?

P. Nusgens (University of Liege, Belgium) This kind of natural ventilation inlet produces a high air exchange rate and we have seen that, for high Archimedes number, the air velocity in the occupied zone may be uncomfortable. Thus it may not be suitable for dwellings. Moreover it would not be very pleasing aesthetically since it extends along the full length of the wall. It may be suitable for industrial buildings however, especially when internal heat loads are important and hence free cooling is welcome.