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INDOOR AIR FLOW PATTERNS

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Criterion of the Corrected Archimedes Number for airflow pattern control in livestock buildings

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1. Introduction

By different authors the ventilation system is considered to be a very important factor to influence the environmental conditions in livestock buildings.[1,2,3] The objective of the ventilation system can be defined as the control of inside gasconcentration, humidity and temperature. To realize this objective, the ventilation system has to accomplish two basic functions : give an efficient control of the ventilation rate and maintain a stable airflow pattern.[4,5] The airflow pattern forms the link between the ventilation system and the microclimate round the animal.[6] Based on experiments it has been shown that the airflow pattern is a key factor in the appearance of temperature gradients in the building.[4,6,7,8] Precise temperature control is unlikely to be possible if the airflow pattern is not controlled at the same time.[10,8] In the field it can be noticed that a lot of the ventilation problem in modern livestock houses are related to a lack of control of the air flow pattern. More precisely the cold air entering the building and dropping onto the animals still is one of the main problems.[6,14]

The process of air replacement in a building is a mechanism of mixing and dilution of contaminated air with clean air. Mostly this incoming air is not isothermal with the room air because of the high internal heat production. The motion of the entering air in such a non-viscous non-isothermal fluid depends on the ratio of the buoyancy to dynamic pressures exterted on its elements.[4] The numerical value of the so called (criterion of the) corrected Archimedes Number is used to relate buoyancy and dynamic pressures in the air, to characterize the direction of the flow, and to define the conditions under which stable flows occur. They showed that the initial path of a ventilating air jet and the stability of the resulting airflow pattern may be determined by calculating the Corrected Archimedes Number, AR_C. It was concluded that the path of air entering a rectangular room through an inlet just beneath the ceiling remains horizontal if AR_C is below 30 and will fall if it is above 75. Between those values unstable intermediate patterns exist. Stable air flow patterns can be achieved in most slot-ventilated livestock buildings with inlet air speed of 5 m s^{-1} providing outside temperature does not drop below 0°C. Colder temperatures require higher jet speeds but those are difficult to achieve.[4] These conclusions where made on results obtained in an experimental section of a simulated livestock building 3.1 m long, 7.6 m wide and 2.1 m to the eaves. It had one transparant end wall and animal heat production was produced by simulated pigs.[4]

In literature the concept of AR_C and its validity was confirmed for other test facilities or theoretical examples. Barber et al. (1982) also considered the Archimedes number, together with the Jet Momentum number, as criteria for predicting stability of air flow patterns in livestock buildings. He concluded both criteria must be met simultaneously if good ventilation is to be ensured.[13] Leonard and Mc Quitty (1985) did measurements in a full-scale experimental facility with simulated pigs in it.[9] They agreed with the value of $AR_C \leq 30$ to predict the entering air to remain horizontal. For most practical situations however they believed a considerably higher value of ARC could be accepted, certainly for full-width continuous slots or inlets adjacent to the ceiling.

From this previous work in literature it can be concluded that the criterion of the Corrected Archimedes Number, AR_C, is saying that : air entering a rectangular room through an inlet just beneath the ceiling remains horizontal if AR_C is below 30 and will fall if it is above 75.

2. Objective

In literature the importance of ventilation rate and airflow pattern for inside climate control in livestock buildings is well-described.[3-18] Despite their importance, neither of these variables is controlled in today's livestock housing. Even the most modern controllers are regulating the voltage to the fan while it is known that this is no good measure for the produced ventilation rate.[14,15] It has also been shown from large scale measurements in commercial buildings that consequently the inside temperature control is not achieved.[15] No buildings use an active airflow pattern control system. If inlet valve controllers are used, they only use one or two temperature sensors without any well-proven criterion. The AR_C-criterion has been tested and measured in experimental facilities and these results were confirmed by experience in commercial barns. In none of the previous work real measurements were done in a commercial building with living animals in it. The objective of this paper is to find out whether the criterion of AR_C is valid in a commercial building, with different dimensions, compared to previous experimental work, with a specific air inlet system and with living animals in it.

3. Method

3.1. *The AR_C-criterion*

The Corrected Archimedes Number as it has been described by Randall and Battams (1979)[4] and confirmed by other authors[9,13] is defined explicitly as:

$$AR_C = \frac{5.89\ a\ b\ B\ H\ (B+H)\ (T_{hs}-T_o)}{V^2\ (546+T_{hs}+T_o)} \qquad (1)$$

To evaluate the validity of the AR_C-criterion the value of AR_C must be calculated. In the definition of AR_C the variables b, B, H and T_{hs} can be considered constant in the measurements. Indeed the horizontal dimension of the inlet vent, b, the dimensions of the building, B and H, the temperature of the stock on the floor, T_{hs}, do not change. The variables that have to be measured continuously are the height of the vent a, the temperature T_o of the incoming air and the volume flow rate V. At the same time the airflow pattern must be recorded.

3.2. *Measurement Materials*

A compartment of a commercial livestock building with 5 full-slattered cages of 12 piglets (30 kg) in each was used. The compartment was 13.5 m long, 3.0 m wide, 2.3 m to the inside eave and 4.54 m to the inside ridge (Fig. 1). The slope of the ceiling was 30 % and a fan, in a chimney, was placed at 2.75 m from the ouside wall. The fan is controlled accordingly to a proportional controller as described in literature.[8, 14, 15] Air is taken from a corridor over a very small inlet valve with a width of 0.95 m, near to the ceiling at a height of 2.46 m and positioned above the door of the compartment (Fig.1). The length of the inlet valve is 1.0 m and its fixed position is regulated by hand.

The position of the air inlet valve is measured by a calibrated potentiometer (output 0 - 10V). From this measurement the vertical dimension of the air inlet, a, can be calculated with an accuracy of 0.002 m The temperature of the air entering the compartment is measured with an integrated Anolog Device sensor (type AD 590) with an accuracy of 0.02°C and a time constant of 240 s.[8] Measurement results are abbreviated at an accuracy of 0.1°C. The sensor to measure temperature of the air entering the compartment was positioned just above the movable air inlet valve (Fig. 1). Volume flow of air through the inlet was measured using the ventilation rate sensor based on the described combination of a flow sensor, a pressure sensor and microprocessor-stored calibration curves.[8, 16] Calibration was done on an installation built accordingly to the DIN Briti standards. It was positioned in the chimney, just after the fan (Fig. 1), and has an accuracy of 30 m^3/h. The whole building was very carefully closed up with silicone rubber to prevent any leakage (between isolating plates at the eaves, in the ridge, the door, ...) in case of normal pressure differences (0 - 6 mm H_2O) The volume flow rate measured in the chimney must be the same as the one coming through the inlet valve. It was shown[8] that the time-difference between the two of them was less than 30s.[8] All the measured values and the time were recorded in a digital way every two minutes at a Mess & System 1000 datalogger.

To visualise the airflow pattern a smoke generator was constructed that could be tended from a distance.[17] The specific weight of the smoke is about the same as the specific weight of air. To be sure that the temperature of the smoke is the same as the entering air, the smoke generator is positioned in the corridor (Fig. 2). In this way the incoming air and the smoke are mixed up before entering the compartment. During the tests there was just enough light in the compartment to observe the airflow pattern coloured white by the smoke. To record the way followed by the white-coloured air, the wall opposite to the observator was covered with black plastic foil. Afterwards a grid was made on this black wall by using white tape. The 0.20 m squares of this grid got coordinates each of them as shown in figure 3. After the observer had given a smoke shot from the control panel, he noted down the coordinates of the squares where the air jet was passing and the time. To make sure the observer knew the exact time at which the datalogger was, every two minutes, registrating, he was informed by the datalogger's clock-time at a display in the control panel.

The noted data of the observer were the data-input for a computerprogram on a Tektronix 4052A which reproduced the airflow pattern as shown in figure 4. At the same time the recorded data were read by the program from the datalogger's tape and the corresponding AR_C-values were calculated using formula (1). The air velocity at position of the air inlet vent was calculated from the measured ventilation rate and the measured vertical dimension of the inlet vent :

$$v = \frac{V}{0.66\ a} \qquad (2)$$

As mentioned above the ventilation rate is measured with an accuracy of 30 $m^3\ h^{-1}$ and the position of inlet valve with an accuracy of 0.002 m. Consequently the air velocity v will be calculated with an accuracy from 0.04 $m\ s^{-1}$ (for maximal a-value) up to 1.26 $m\ s^{-1}$ (for minimal a-value). It will be seen that this accuracy is far good enough for the objectives of this study.

There was a good contrast between the white coloured air entering the compartment and the black wall with the white coordinate grid. Therefore a very weak light was sufficient during the tests and the animals showed normal behaviour during the experiment. The advantage of a human observer, compared to a camera, was the observation of animal behaviour that could influence the airflow pattern if not normal. The observer was the same person during the whole experimental work.

It was experienced that the method permitted to measure the airflow pattern with an accuracy of 0.5 m (+0.25 and -0.25 m).

3.3. *Experimental Procedure*

The temperature of the incoming air is strongly related to the outside temperature and can not be changed in such a commercial building. Only the vertical dimension of the inlet vent and the ventilation rate could be changed during the tests. For the measured values of outside temperature, each test consisted of setting the ventilation rate and the inlet valve position. Then there was a waiting period of 20 minutes, to make sure the airflow pattern had become stable, before the smoke shot was given and results were recorded.
92 different tests were done over which the ventilation rate was varied from 200 to 2300 m^3/h, the vertical dimension of the inlet vent, was changed from 0.01 m to 0.35 m and the measured temperature of the incoming air varied from - 2.0°C to 15.0°C. The resulting AR_C-number in these 92 tests changed from 683 to 0.63. All the 92 measured data-files were used in the analysis.

4. Results and discussion

In figures the observed airflow patterns and their corresponding calculated AR_C-number are presented as they resulted from the 92 experiments. This figures illustrate that also in commercial pig houses (13.5 m by 3 m and a sloped ceiling at a mean height of 3. 42 m, figure 1), occupied with living animals and for the circumstances as described above a clear relationship exists between the AR_C (as defined by Randall and Battams, 1979) and the air trajectory. The same confirmation was made by Leonard and McQuitty (1985) from experiments in a room of 5.4 by 7.2 m and a flat ceiling at 1.9 m height in which water filled heating pads were used to simulate the presence of animals. The authors suggested care in extrapolating the results to much larger rooms because of the effects of the room boundaries.

We will now analyse how well the AR_C-number is related to the initial path and the final part of the airflow in such a commercial pig house.

4.1. Relationship between AR_C and the initial path

To look for a relationship between AR_C and the initial path of the air it is necessary to quantify this observed initial path. A theoretical possibility is the angle Á between the incoming air and a horizontal plane (figure 6). The problem is that one needs a linear part at the initial air path and that it is not always clear where this linear part is ending. Especially not in case the incoming air is falling down immediately. Another possible way to quantify the initial air path is the y-coordinate (y_{max}) of the highest point that is reached by the air trajectory. One can indeed expect that the maximum y-value of the observed (x,y)-coordinates of an air trajectory is a measure for the slope of the initial air path. This maximum y-value is unequivocally defined for each air trafectory observed in the way described above. From the datasets it could be seen also that the maximum y-coordinate of the air trajectory is always situated in the first half part of the compartment. In table 1 the AR_C and the maximum y-coordinate are given for the observed air trajectories as shown in figures 5A and 5B. In figure 7 these values of table 1 are plotted. There are two possibilities to see how strong this relationship is: a non-linear regression or a transformation combined with a linear regression. The main objective of this article is to find whether there is a clear relationship and not to determine this relationship because it will depend on the dimensions, the shape, the construction ... of the building. Therefore a linear regression is used on transformed data.

We have found that a linear least squares regression between $AR_C^{0.25}$ and y-maximum has a R^2-value of 0.8906 for the following equation (figure 8):

$$AR_C^{0.25} = 10.21303 - 2.15857 \cdot y_{max} \qquad (3)$$

The conclusion can be drawn that in this type of commercial building occupied with living animals, the AR_C-number is strongly related to y_{max}: the maximum height-coordinate of the observed air trajectory in the building. Using (the inverse relationship of) equation 2 the maximum height of the air trajectory can be predicted from the AR_C-number and is compared to the observed values of y_{max} (Table 2). It gives an indication of how accurate the maximum height of the air trajectory can be predicted from the AR_C-number. If this y_{max} is accepted as a measure for the slope of the initial path, then we can also conclude that AR_C is a measure for the initial path.

4.2. Relationship between AR_C and the final path

4.2.1. Relationship between AR_C and the slope of the final path

The slope of the final path is measured by the angle Á that is defined as: the angle (radial) between the connectionline of start- and endpoint of the air trajectory and on the other side a horizontal plane positioned through the first point of the trajectory (figure 9). As shown in figure 9, this angle can have a positive or a negative value.
For the observed air trajectories the values of the AR_C-number and this corresponding angle are shown in table 3 and figure 10. Similar to the above regression a transformation is combined with a linear least square regression with the purpose to find a relationship. The best, curve fit resulted in a R^2 value of 0.9149 for the equation (figure 11):

$$AR_C^{0.25} = 1.41522 - 266372 \cdot Á \qquad (4)$$

The conclusion can be drawn that the AR_C-number is also strongly related to the angle Á as defined above. In other words the AR_C-number is also related to the final path of the air jet.
From these results it might be expected that the AR_C-number is also related to the final position of the air trajectory. This position can be situated by using a pair of coordinates: x and y. x is the horizontal distance from the air inlet to the final position of the air path. y is the vertical distance from floor level to the final position of the air trajectory.
Similar to the analysis given above a transformation and a linear regression is used to look for relationship. The best fit with an R^2-value of 0.9043 results in the equation:

$$AR_C^{0.25} = 4.74214 - 0.27047 \cdot x - 0.29287 \cdot y \qquad (5)$$

The conclusion can be drawn that the AR_C-number is also related to the final position of the air trajectory.

In general it can be seen that the values of the AR_C-number differ a little bit from those obtained by Randall and Battams (1979). This can be explained by the following differences:

- the scale of the room: our experiments were done in a large commercial compartment up to 13.50m long.
- the sloping ceiling in this commercial building compared to the flat ceiling in the previous test facilities.
- only one single air inlet at one side of the building instead of two air inlets at a control position.
- living animals respond in a different way to an airflow pattern than simulated pigs.
- distance between the air inlet and the fan.

Because of these differences the critical value of the AR_C-number, to prevent the air to fall to the livestock, can be different for the different stables. Randall and Battams (1979) stated that the air entering a rectangular room through an inlet just beneath the ceiling remains horizontal if AR_C is below 30 and will fall above 75. Although these critical AR_C values will be influenced by the parameters related to the building, as mentioned above, the value of $AR_C = 30$ would also be acceptable for these commercial buildings. This value has also been confirmed as acceptable for most practical situations by Leonard and McQuitty (1985).

Conclusions

By doing these experiments a useful method has been described to quantify and to study the airflow pattern in commercial buildings occupied with living animals.

From these 92 experiments the conclusion can be drawn that also in commercial pig houses with a floor surface of 13.5 by 3 m, with a sloped ceiling at a mean height of 3.40 m, with the air inlet at one side in the wall and a single outlet fan in the opposite ceiling-side, for the conditions in the experiments (inlet velocity from 0.3 to 6.0 m/s, temperature of the incoming air from -2.0 to 15.0°C), the AR_C-number as defined by Randall and Battams (1979) is clearly related to the air trajectory.

The AR_C has been found to be related to the maximum height reached by the air path which might be a measure for the initial path of the air. AR_C is a good measure for the angle between the connection line from starting point to final point of the trajectory and a horizontal plane. Finally the AR_C-number has been found to be related to the final position of the trajectory.

The critical values of AR_C, smaller than 30 for a horizontal air path and $AR_C > 70$ for falling air with unstable air flow pattern between them are also acceptable for these commercial buildings.

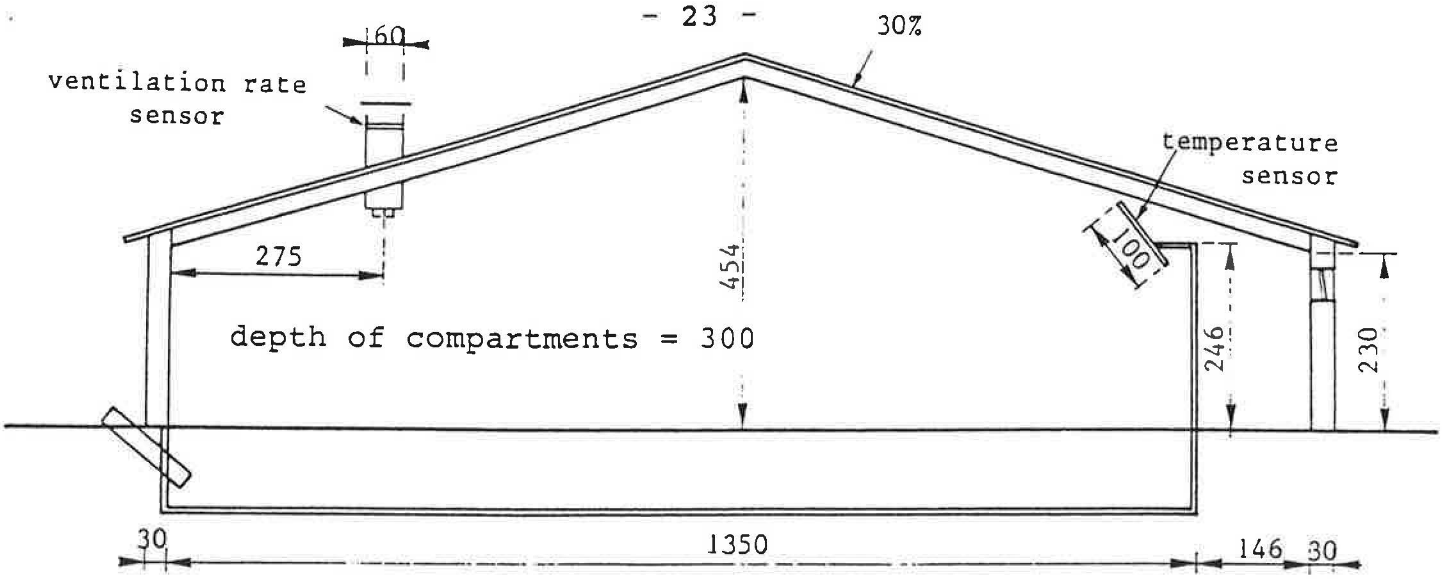


Figure 1 : Section of the commercial livestock building with its dimensions.

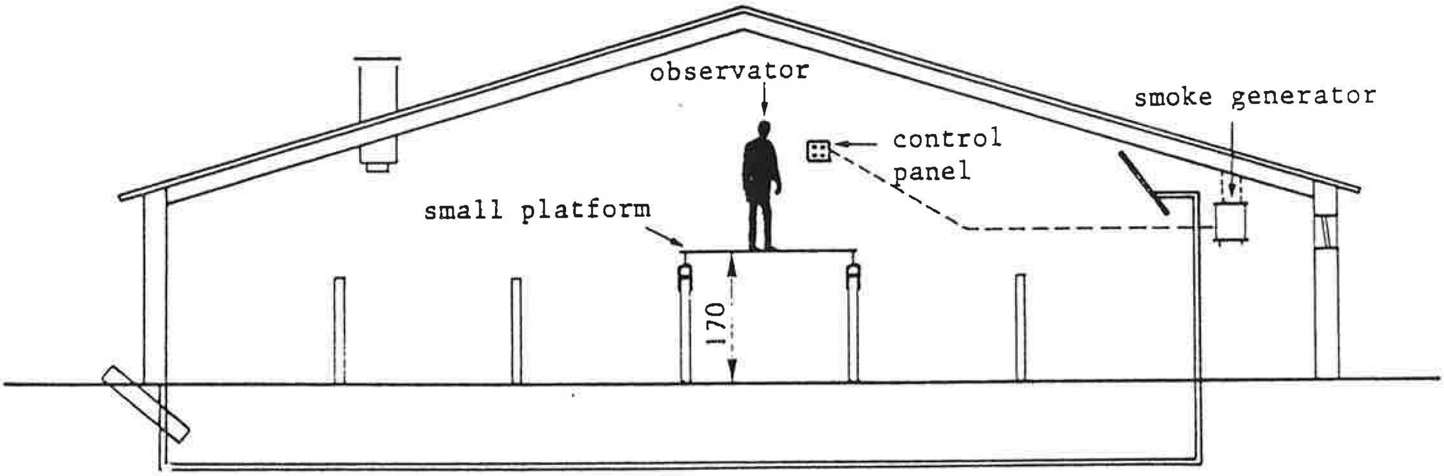


Figure 2: Schematic representation of the observator above the stock and of the smoke generator tended from distance.

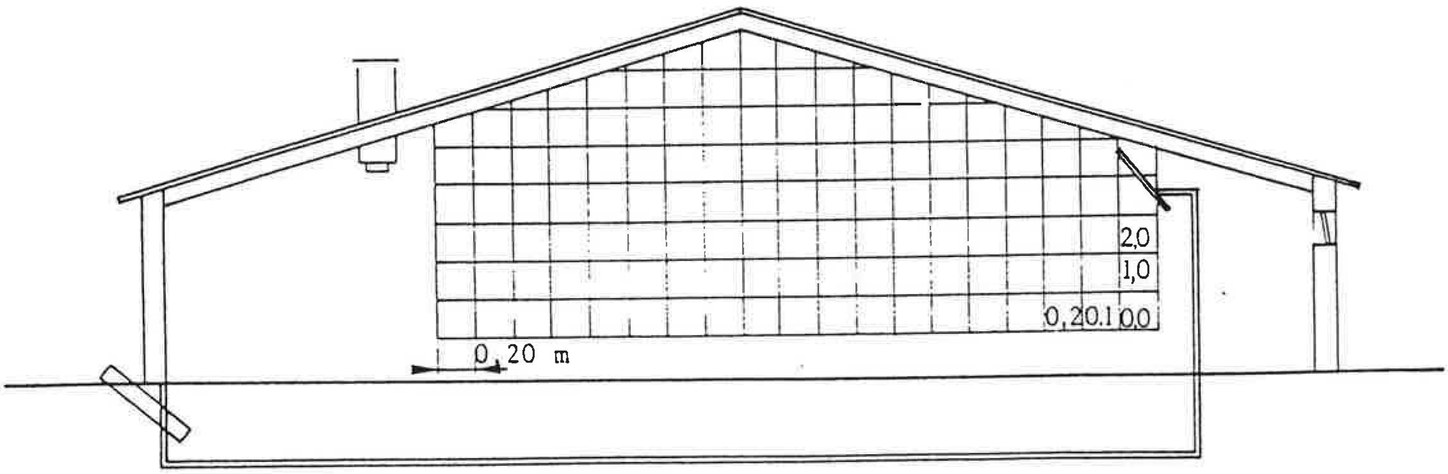
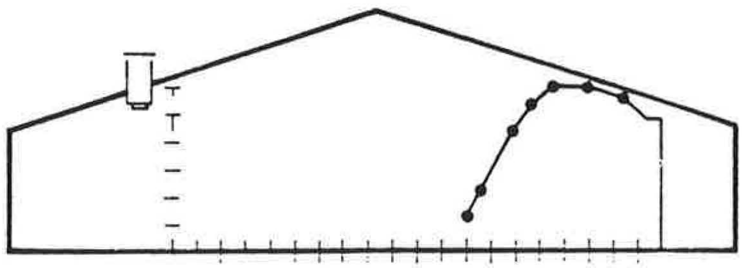
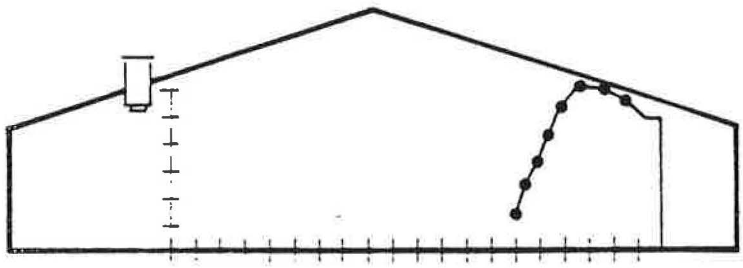


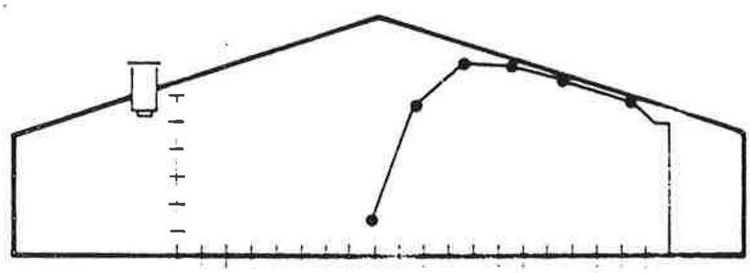
Figure 3 : the coordinate grid on the black wall to locate the airflow pattern.



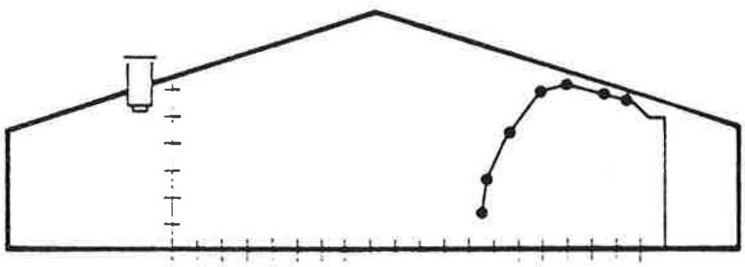
v = 586
a = 25
To = 6.4
Ths = 30
Ar_C = 100.39



v = 603
a = 20
To = 0.8
Ths = 30
Ar_C = 95.85



v = 330
a = 10
To = 14.1
Ths = 30
Ar_C = 84.65



v = 616
a = 35
To = 14.3
Ths = 30
Ar_C = 83.54

Figure 4 : Computergraphic representation of the observed airflow pattern and corresponding calculated values of the Ar_C-number.

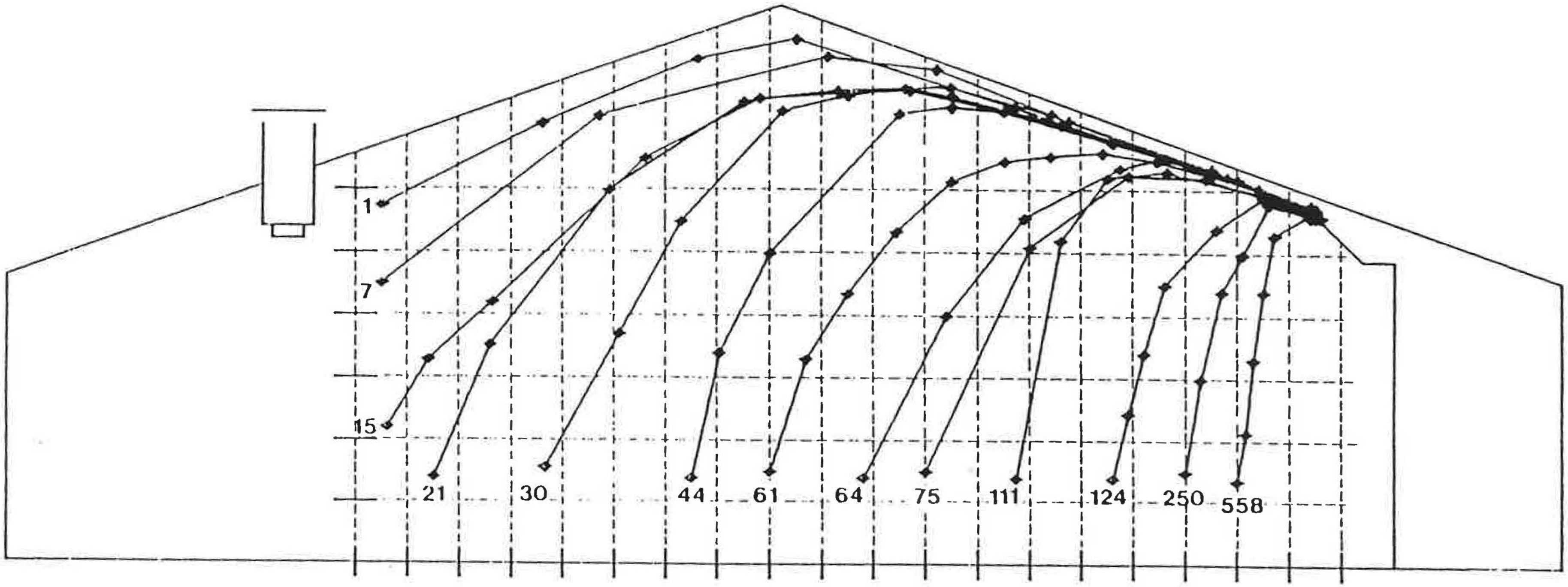


Figure 5 : Representation of the calculated value of Ar_C and the observed airflow pattern (1/3 of the total of 92 experiments).

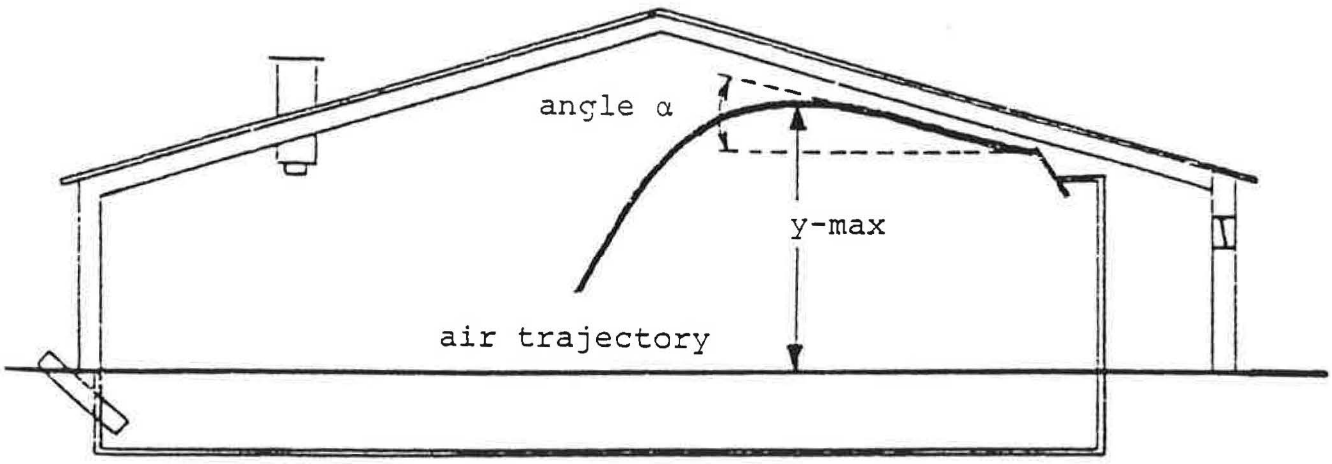


Figure 6 : angle α of the incoming air and y-max coordinate of the initial air path.

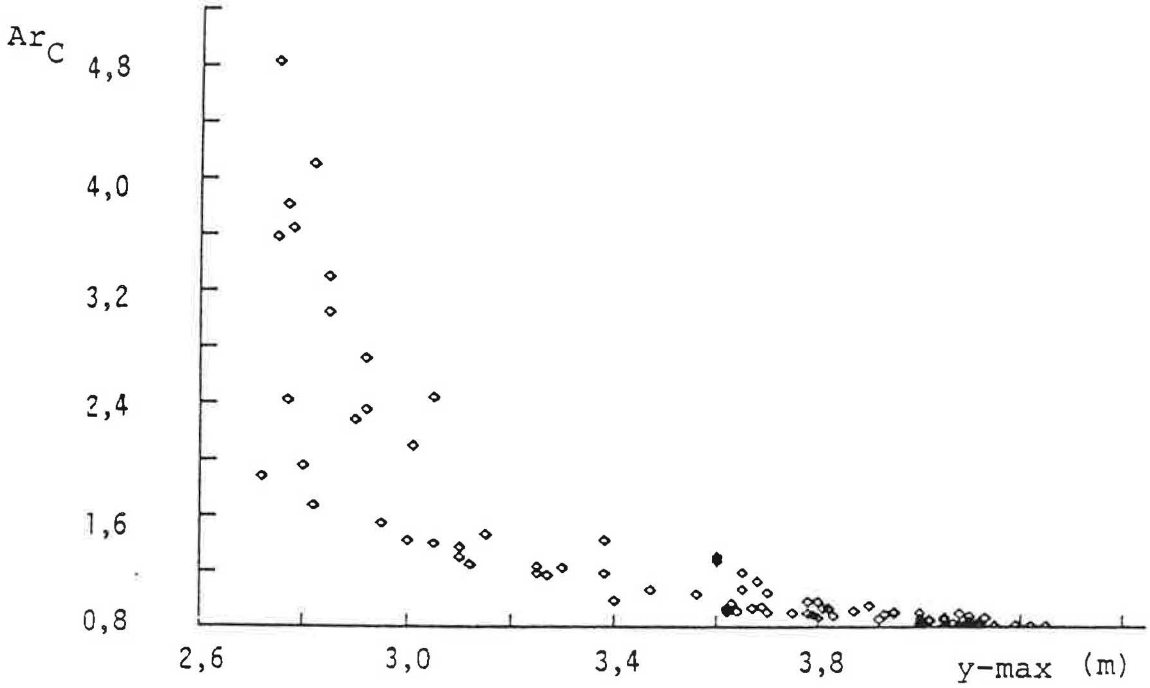


Figure 7 : Ar_C-number plotted against y-max value.

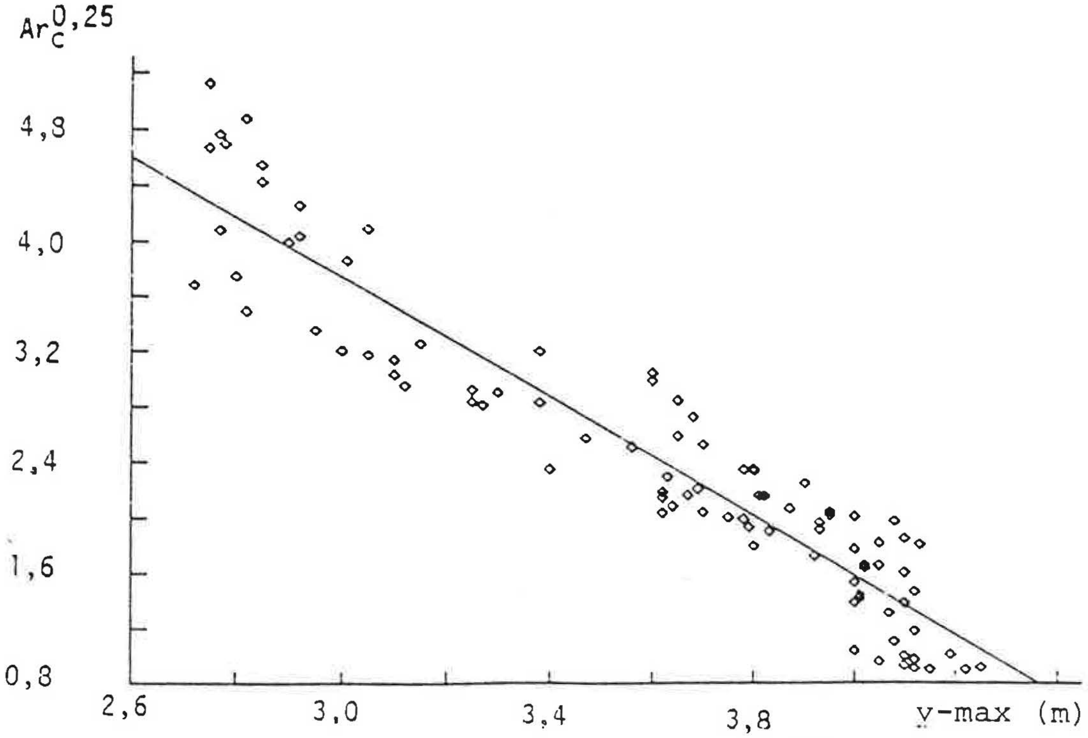


Figure 8 : Linear regression between $Ar_C^{0.25}$ and y-max.

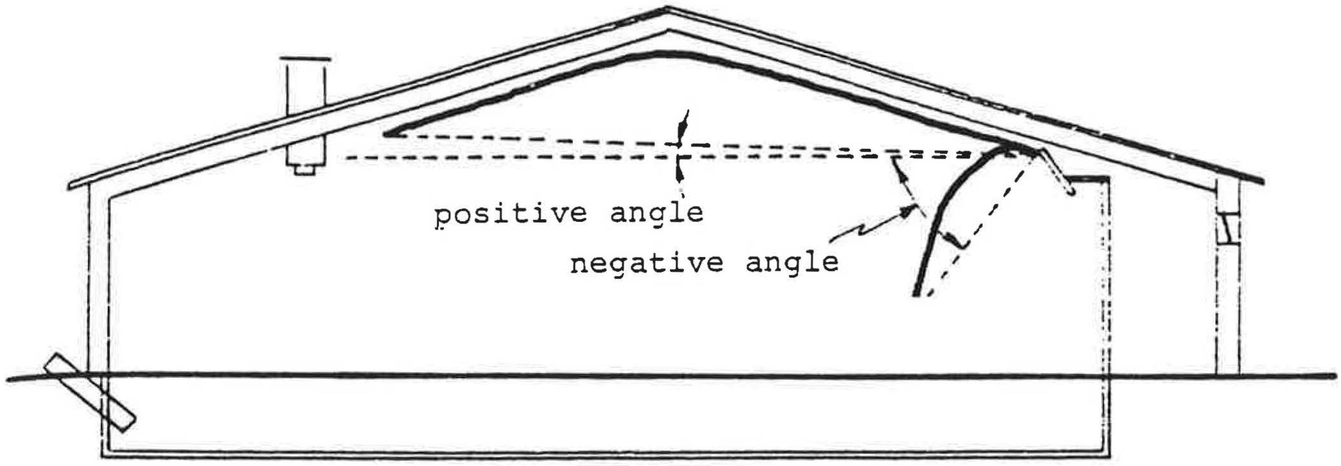


Figure 9 : Angle α with positive or negative value as a measure for the air trajectory.

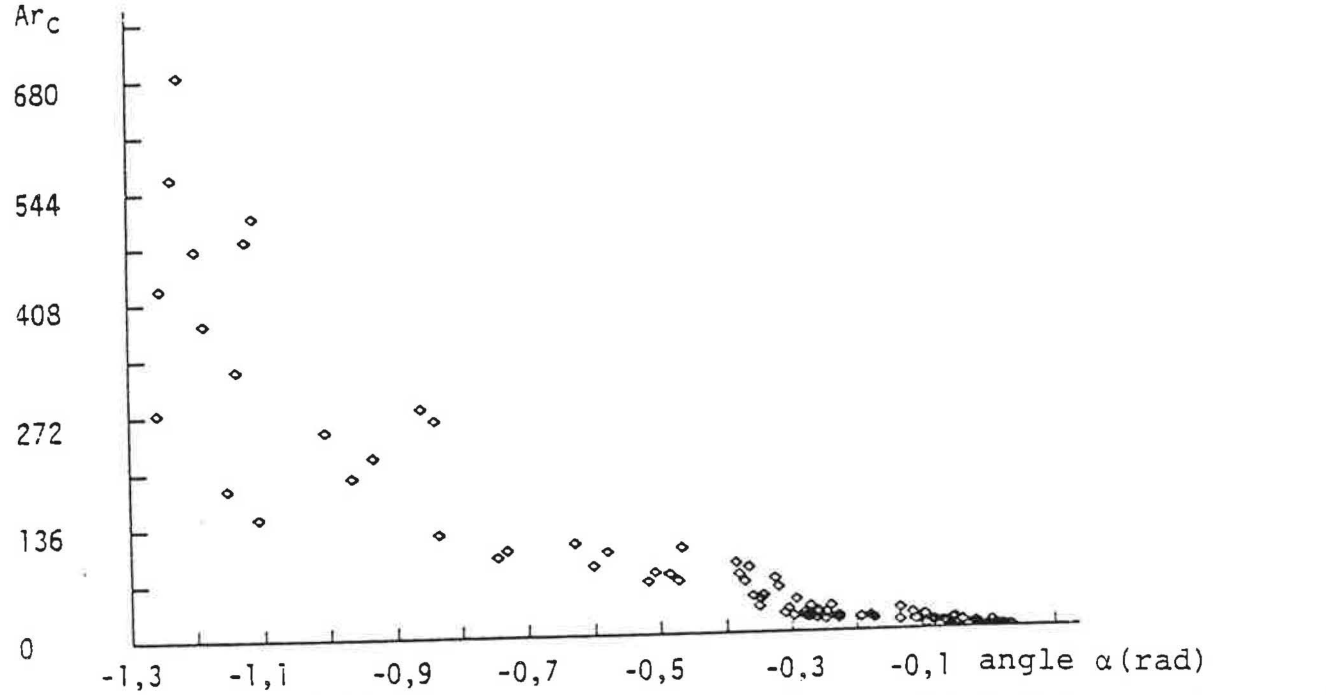


Figure 10: Ar_C plotted against corresponding angle α for the observed air trajectories.

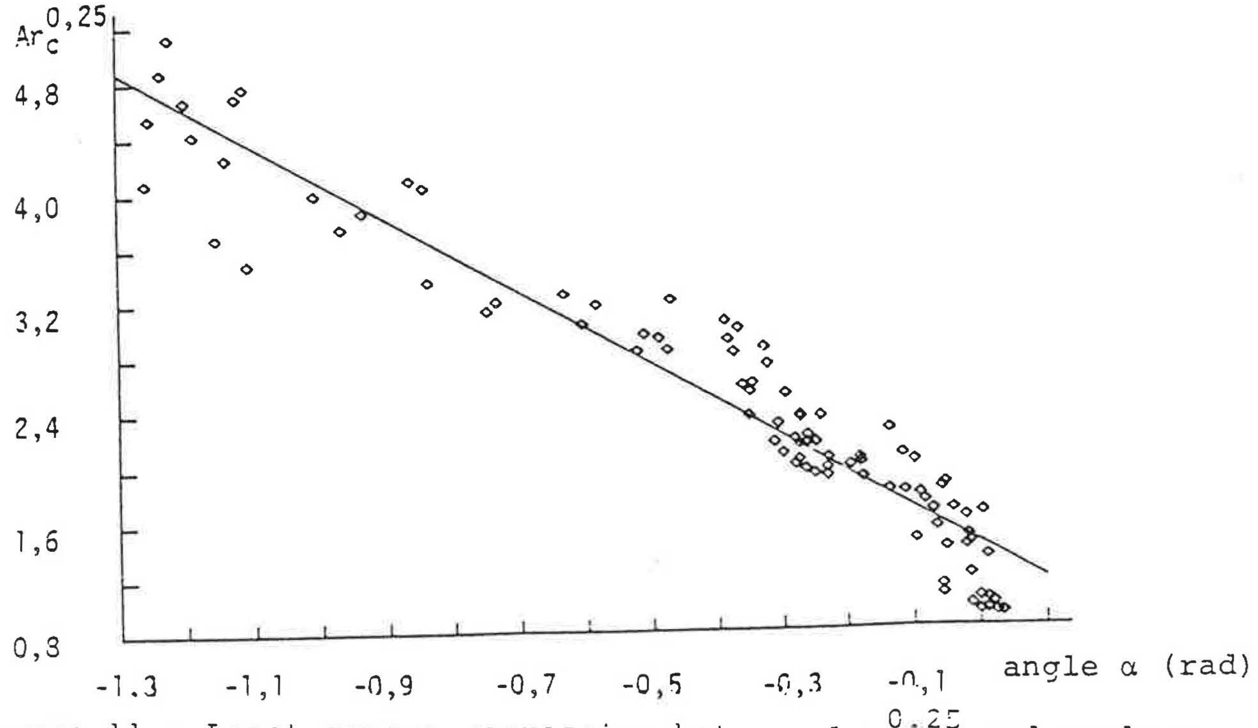


Figure 11 : Least square regression between $Ar_C^{0.25}$ and angle α.

Table 1 : Ar_C-numbers and the maximum y-coordinate of the air trajectories presented in figure 5.

Ar_c	y-max (m)	Ar_c	y-max (m)	Ar_c	y-max (m)
683,089	2,75	61,879	3,27	12,791	3,83
558,919	2,82	54,530	3,68	11,439	4,10
509,909	2,77	44,208	3,65	10,670	4,05
481,487	2,78	43,240	3,47	10,407	4,13
471,154	2,75	40,187	3,70	10,197	3,80
423,303	2,85	39,045	3,56	9,678	4,00
379,837	2,85	30,286	3,40	8,635	3,92
324,976	2,92	30,041	3,80	7,457	4,02
276,999	3,05	29,790	3,78	7,341	4,05
274,209	2,77	29,390	3,80	6,959	4,02
262,765	2,92	27,270	3,63	6,440	4,10
250,657	2,90	25,102	3,90	5,363	4,00
219,173	3,01	23,337	3,69	4,481	4,12
194,372	2,80	22,375	3,62	4,253	4,01
181,641	2,72	21,511	3,67	3,931	4,01
146,694	2,82	21,289	3,81	3,628	4,00
124,893	2,95	21,224	3,82	3,543	4,10
111,140	3,15	20,810	3,62	2,871	4,07
104,366	3,00	18,459	3,64	1,871	4,12
104,264	3,38	17,918	3,87	1,424	4,08
100,393	3,05	17,180	3,95	1,118	4,00
95,845	3,10	16,974	3,70	0,997	4,19
84,651	3,60	16,824	3,62	0,954	4,10
83,540	3,10	16,168	3,95	0,857	4,12
78,519	3,60	16,005	4,00	0,806	4,05
75,037	3,12	15,707	3,75	0,709	4,10
72,121	3,25	15,376	3,78	0,677	4,25
70,475	3,30	14,864	4,08	0,650	4,12
64,728	3,65	14,585	3,93	0,630	4,22
64,146	3,25	13,631	3,79	0,628	4,15
63,630	3,38	13,188	3,93		

Table 2 : Predicted y-max values calculated from Ar_C with equation (2) compared to the obeserved y-max values.

y-max observed (m)	y-max pred. (m)	y-max observ. (m)	y-max pred. (m)	y-max observ. (m)	y -max pred. (m)
2,75	2,36	3,27	3,43	3,83	3,86
2,82	2,48	3,68	3,47	4,10	3,88
2,77	2,53	3,65	3,54	4,05	3,89
2,78	2,56	3,47	3,54	4,13	3,90
2,75	2,57	3,70	3,56	3,80	3,90
2,85	2,63	3,56	3,57	4,00	3,91
2,85	2,69	3,40	3,64	3,92	3,94
2,92	2,76	3,80	3,65	4,02	3,97
3,05	2,84	3,78	3,67	4,05	3,97
2,77	2,85	3,80	3,65	4,02	3,98
2,92	2,87	3,63	3,67	4,10	3,99
2,90	2,89	3,90	3,69	4,00	4,03
3,01	2,95	3,69	3,71	4,12	4,06
2,80	3,00	3,62	3,72	4,01	4,07
2,72	3,03	3,67	3,73	4,01	4,08
2,82	3,12	3,81	3,74	4,00	4,09
2,95	3,18	3,82	3,74	4,10	4,10
3,15	3,23	3,62	3,74	4,07	4,13
3,00	3,25	3,64	3,77	4,12	4,19
3,38	3,25	3,87	3,78	4,08	4,23
3,05	3,26	3,95	3,79	4,00	4,26
3,10	3,28	3,70	3,79	4,19	4,27
3,60	3,33	3,62	3,79	4,10	4,27
3,10	3,33	3,95	3,80	4,12	4,29
3,60	3,35	4,00	3,80	4,05	4,29
3,12	3,37	3,75	3,81	4,10	4,31
3,25	3,38	3,78	3,81	4,25	4,31
3,30	3,39	4,08	3,82	4,12	4,32
3,65	3,42	3,93	3,83	4,22	4,32
3,25	3,42	3,79	3,84	4,15	4,32
3,38	3,42	3,93	3,85		

Table 3 : Ar_C and the angle α for the observed air trajectories in the 92 experiments.

Ar_c	angle α (rad)	Ar_c	angle α (rad)	Ar_c	angle α (rad)
683,089	-1,2216	61,879	-0,3723	12,791	-0,1746
558,919	-1,2337	54,530	-0,3213	11,439	-0,0502
509,909	-1,1111	44,208	-0,3441	10,670	-0,0555
481,487	-1,1227	43,240	-0,3597	10,407	-0,1348
471,154	-1,1987	40,187	-0,3485	10,197	-0,1113
423,303	-1,2519	39,045	-0,2938	9,678	-0,0882
379,837	-1,1863	30,286	-0,3507	8,635	-0,0812
324,976	-1,1381	30,041	-0,2721	7,457	-0,0389
276,999	-0,8612	29,790	-0,2400	7,341	-0,0688
274,209	-1,2578	29,390	-0,2713	6,959	0,0055
262,765	-0,8406	27,270	-0,3055	6,440	-0,0200
250,657	-1,0056	25,102	-0,1343	5,363	-0,0642
219,173	-0,9345	23,337	-0,2598	4,481	-0,0168
194,372	-0,9665	22,375	-0,2801	4,253	-0,0958
181,641	-1,1539	21,511	-0,3114	3,931	-0,0142
146,694	-1,1071	21,289	-0,2477	3,628	-0,0200
124,893	-0,8354	21,224	-0,2602	3,543	-0,0500
111,140	-0,6300	20,810	-0,2727	2,871	0,0111
104,366	-0,7321	18,459	-0,2980	1,871	-0,0144
104,264	-0,4674	17,918	-0,1150	1,424	-0,0558
100,393	-0,5808	17,180	-0,2280	1,118	-0,0555
95,845	-0,7462	16,974	-0,1794	0,997	0,0000
84,651	-0,3854	16,824	-0,2736	0,954	0,0122
83,540	-0,6027	16,168	-0,0964	0,857	0,0201
78,519	-0,3654	16,005	-0,1781	0,806	-0,0133
75,037	-0,5080	15,707	-0,2790	0,709	0,0122
72,121	-0,4855	15,376	-0,1942	0,677	0,0110
70,476	-0,3805	14,864	-0,2297	0,650	0,0000
64,728	-0,3264	14,585	-0,2625	0,630	0,0334
64,146	-0,4729	13,631	-0,2489	0,628	0,0250
63,630	-0,5189	13,188	-0,2292		

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Symbols

a	vertical dimension of vent, m
b	horizontal dimension of a vent, m (b = 0.95 m)
AR_C	Archimedes number for a room based on the effective area of a vent (symbol after Randall)
B	width of room (side containing the vent), m
H	height of room, m (H = 2.73 m)
L	length of room, m
T_{hs}	temperature of the heat surface, °C
T_0	temperature of air entering a room (i.e. temperature of outside air), °C
v	velocity at the inlet vent, ms^{-1}
V	volume rate of air flow through the building (through the inlet), $m^3\ s^{-1}$
y_{max}	maximum y-coordinate of the observed points in the air trajectory, m

5.86 = 0.6 . g (accelaration due to gravity, $m^2\ s^{-1}$)