COMFORT PROBLEMS AND ENERGY LOSSES AT SHOP ENTRANCES – FIELD INVESTIGATIONS AND NUMERICAL SIMULATIONS

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ABSTRACT

In order to give some guidance for the optimization of shop entrances regarding comfort and energy savings, a project was launched by the City of Zurich. The project covers field investigations in 12 shops with different entrance types, and analytical and numerical investigations (CFD) for complementary results.

The emphasis of this work was on the interaction between the situation at tne entrance for different technical local solutions with other factors of importance like building ventilation, building tightness and combination with other entrances. As a main result for the practitioner, a lot of recommendations can be drawn from these investigations and will also serve as the basis for governmental guidelines.

KEYWORDS

Air curtain, air flow pattern, comfort, cross ventilation, natural convection

1. INTRODUCTION

Shop entrances should be very attractive to customers and therefore be as much open as possible, as wished by the shop owners, even in the cold season. From the airflow point of view, the outdoor climate will influence considerably the indoor climate, which should be designed to provide good comfort to the customers and the employees. In our latitudes this will cause problems in the cold season due to draft and the perceiving of cold air, at least near the entrance.

Several devices have been developed to reduce these problems, among which the most popular are a wind shield using two successive doors, a revolving door and different kinds of air curtains (see Figure 1).

Particularly air curtains became quite popular in many countries, and different types have been designed in the past to prevent a cold climate inside the shop; they only work well if certain building requirements are fulfilled.

On the other hand, a warm air curtain at an entrance can be seen, at least partly, as a waste of energy. This is a regulatory issue in Switzerland, and therefore, air curtains tend to be forbidden.

It was unclear however, whether revolving doors or other solutions really provide a superior energy performance, as it was widely believed.

To illuminate such open questions, a project was initialized by the city government of Zurich, and sponsored by other governmental organizations in Switzerland. This project covered:

- an experimental investigation of 12 different solutions for shop entrances, including different types of air curtains, revolving doors and normal doors. Temperature and velocity profiles at different locations were measured.
- A questionnaire was prepared and filled by people working in these shops to assess comfort perceived by individuals.
- Complementary results were obtained using analytical investigations for air flow through large openings and numerical simulations (by Computational Fluid Dynamics – CFD) for different types of air curtains and building parameters like tightness or pressurization. Emphasis of the CFD calculation was on the interaction of air curtains with other factors of large importance in buildings.
- Energy losses of different entrance solutions have been compared.

The case of large openings without wind can be treated in a simplified way, whereas the inclusion of air curtains or revolving doors cannot be done analytically; the performance of different air curtains and the combination with wind effects was studied numerically by CFD, and results for revolving doors are derived from experiments done elsewhere.

2 AIR FLOW IN AN OPEN ENTRANCE

First of all it is very instructive to study the flow behavior at an open entrance without special devices attached.

Openings between an inside space and outdoor allow different air flows depending on the temperature difference between inside and outside and on the external wind conditions.

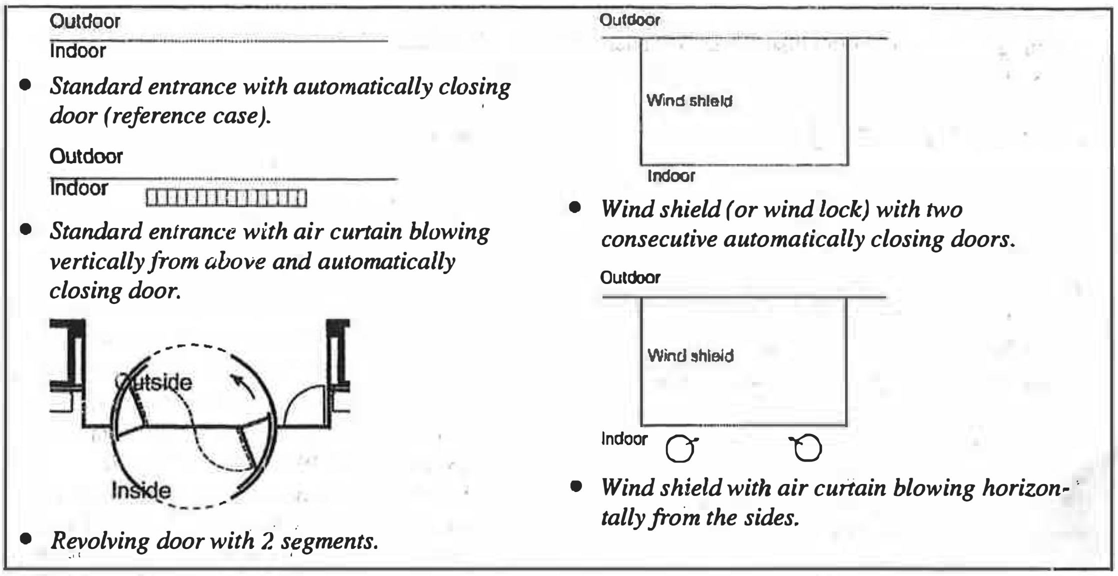

Figure 1: Ground plans with different entrance situations of interest.

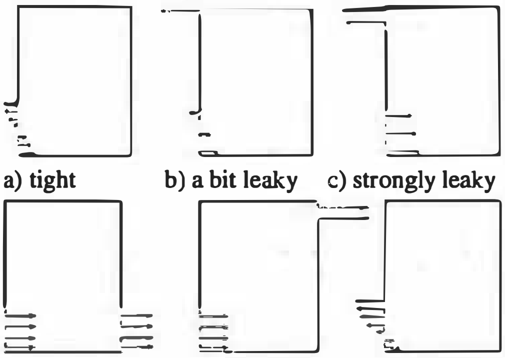

Figure 2: Air flow through different configurations of 1-2 openings.

Figure 2 shows the most interesting types of air flow:

1. With temperature difference between inside and outside (warm inside, cold outside) and no wind:
   - If there is only one entrance, warm air leaves to the outside through the upper part, and cold air enters the inside space through the lower part of the opening (see Figure 1a). Net flow through the opening is zero, and velocities are in the range up to 1 m/s.
   - If there is more than one opening on the same height, the same occurs in each opening.
   - If there is more than one opening on different height levels, air flows through the whole building from below to above (see Figures 1b and 1c). Velocities can be as high as 5 m/s! The field investigation shows that such air flows are found quite frequently, particularly with open stair cases or elevator wells.
2. With external wind:
   - If there is only one entrance:
     - * not much happens if the entrance is small and well hidden to the wind, except for some gusts that give some blows.
     - * if the entrance is large and much exposed to the wind, particularly at a corner of a building, wind-induced cross-flow through this only opening can occur.
   - If there is more than one opening, at any height, strong air flows through the whole building occur depending on the overall flow resistance (see Figures 1d and 1e).
3. If the ventilation system is run with non-zero mass balance (over- or under-pressurized), there is a net flow through the opening, but often the flow is still bi-directional.
4. Combinations of the above.

The flow profile in the opening plane can be described analytically using a simplified approach based on the Bernoulli equation for inviscid flow [1-3]. For the bi-directional flow in the case of one single opening the following equations (with all quantities in SI units) can be derived for the maximum velocity u_{max}, the flow rate $\dot{V}$ in each direction and the associated heat loss Q respectively, as a function of the door height H, door width B and temperature difference ΔT between inside and outside

$$u_{max} = 0.6\sqrt{20(H/2)\frac{\Delta T}{273}},$$

assuming a typical opening discharge coefficient of 0.6. And

$$\dot{V} = 1/3\, u_{max}\, B\, H = 0.2\, \sqrt{\frac{10}{273}}\, B\, H^{1.5}\, \Delta T^{0.5}$$

$$Q = \rho\, \dot{V}\, c_p\, \Delta T = 230\, \sqrt{\frac{10}{273}}\, B\, H^{1.5}\, \Delta T^{1.5}$$

where c_p is the heat capacity of air. The equations show the following dependencies:

- the flow rate depends only weakly on the temperature difference; this means however also that there is a considerable flow even at small temperature differences.
- the flow rate depends linearly on the door width, but stronger on the door height. That means a door higher than necessary leads to a much higher energy loss.
- the heat loss depends also strongly on the temperature difference (prop. $\Delta T^{1.5}$). The energy problem increases progressively with lower outdoor temperature.

Figure 3 shows some of these relationships.

The field investigations have shown that at the entrance often cold air only is entering the building (at a balanced ventilation system). That means that at some other locations in the building the same amount of warm air is leaving.

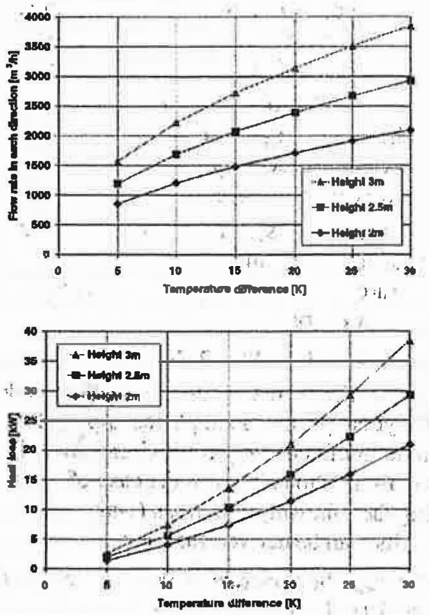

Figure 3: Bi-directional flow through single opening per width of 1m. Above: Flow rate vs. temperature difference. Below: Heat loss vs. temperature difference. Each dependence is shown for three door heights.

This situation is encountered frequently in old multi-storey buildings, most probably due to leaky windows, elevator wells and so on.

In those cases the losses can be much higher. The analytical treatment presented above can be extended easily to such cases [3] to demonstrate the importance of preventing such effects. Two openings are assumed at different height levels; the upper one stands for all the distributed leaks. Figure 4 shows similar losses for opening sizes of $2m^2$ at the lower and $1m^2$ at the higher level.

This example shows that for the same entrance area the loss increases from 11.5 kW for the tight building (door height of 2m and temperature difference DT of 20K in Figure 3) to 60-80 kW for the leaky building (for height differences within 15-25m and DT of 20K in Figure 4), depending on the height of the second opening. This is not an example of an unrealistic academic case, but such flow and loss rates were indeed found in one of the 12 cases for a building without intentionally opened windows.

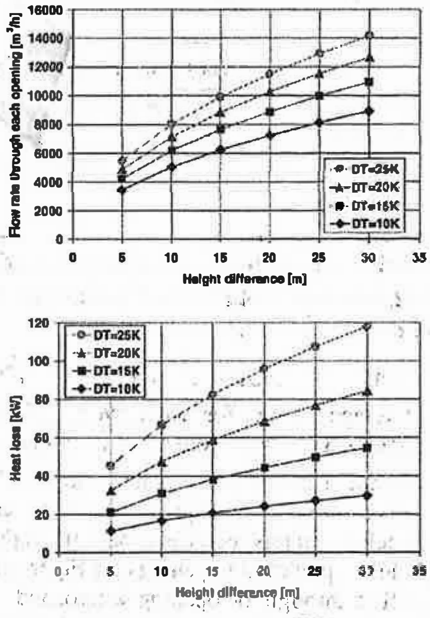

Figure 4: Cross flow in a building through two openings at different heights. Above: Flow rate vs. height difference. Below: Heat loss vs. height difference. Each dependence is shown for four temperature differences.

3. FIELD INVESTIGATIONS

The field studies at different types of entrances should give an overview of the practical importance of several possible influences. 12 shops and department stores of different size downtown

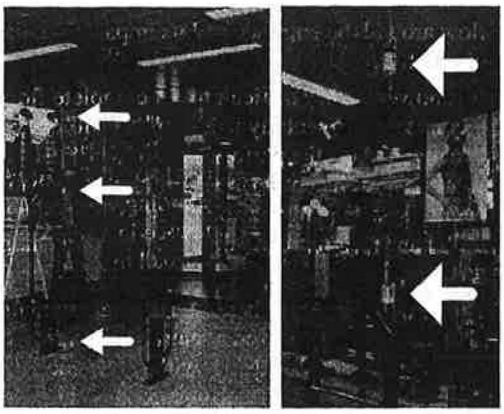

Figure 5: Positioning of temperature monitors.

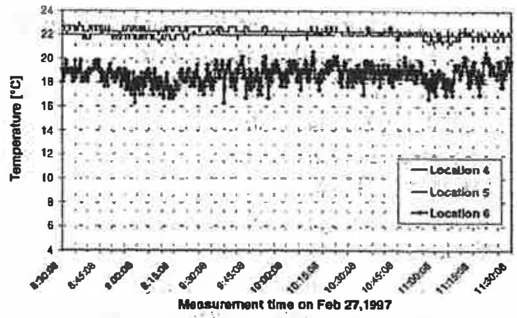

Figure 6: Temperatures in the example of Figure 6 at locations 4-6, 1m from the revolving door, at heights of 0.02m, 1.5m and 2.8m.

	In front of table A			Near entrance			Behind table A		
Height		*Measured*	*Average*		*Measured*	*Average*		*Measured*	*Average*
2.8 m	1	0.08-0.15 m/s	0.1 m/s	4	0.1-0.3 m/s	0.2 m/s	7	0.06-0.12 m/s	0.08 m/s
1.5 m	2	0.1-0.2 m/s	0.1 m/s	5	0.08-0.22 m/s	0.15 m/s	8	0.05-0.12 m/s	0.08 m/s
0.02 m	3	0.07-0.2 m/s	0.1 m/s	6	0.1-0.3 m/s	0.15 m/s	9	0.15-0.25 m/s	0.2 m/s

Table 1: Measured velocities in the above example at monitor points 1-9. Values exceeding 0.2 m/s are highlighted.

Zurich have been chosen as test cases. Standard entrances, wind shields with double door entrances, revolving doors and air curtains of different kinds are found in these shops (see Figure 1).

During half a day in the cold season a number of investigations were carried out:

- temperature measurement at 10 locations (different positions and different heights, usually 0.05m, 1.5m and 2.5-3.0m, see Figure 5) during a couple of hours,
- flow visualization around the entrance by smoke,
- velocity measurements by a portable anemometer at several locations of interest, handout of a technical questionnaire to the technical staff, and a comfort questionnaire to the employees, altogether 40. The latter contained specific questions about their comfort feeling (frequency of draft, perception of the presence of cold air and so on).

Figure 5 shows the positioning of the temperature monitors near the entrance in one case with revolving door. Figure 6 shows the measurement positions in the ground plane in this case.
Table 1 shows the measured velocity values. In this case only moderate values were found.

Figure 7 shows an example of the three monitor points near the revolving door. This result shows clearly that cold air is found inside the revolving door near the entrance, despite the fact that warm air is added to the cold air from the circumferential wall of the revolving door.

Results:

Generally, the reported range of comfort in the 12 investigated shops is very wide and corresponds to a large extent to the measured values of the air temperature and velocities in the shops.

Complete satisfaction was never found, but this cannot be expected regarding human comfort feeling. Nevertheless some shops report very little comfort problems, whereas in other shops the entrance situation leads to heavy complaints.

In any case, working places (which are cashiers in most cases, e.g. place A in Figure 6) should be situated as far as possible from the entrance. If a placement close to the entrance cannot be avoided, a local protection shield like a low wall from the floor to a height of 1.2m should be installed.

The tightness of the entrance is obviously a primary problem. The doors are very often quite leaky even when closed. Cold air can enter at high velocities (1-2m/s). This was observed also at revolving doors.

Air curtains are often used to separate the indoor climate from the outdoor climate. It was found in some cases that the air curtains did not work properly. Reasons are:

- The existence of more than one entrance will deteriorate the shielding performance in two ways:

* if the entrances are at different height levels, there will be a thermal pressure difference
* if there is wind influence, there will be a wind-induced pressure difference

In both cases there can be strong air draft between the entrances even with air curtains.

- A leaky building can lead to net flow across the air curtain
- Over- or under-pressurization due to a (often intentionally) unbalanced ventilation system. The net flow through the entrance can deflect the air curtain allowing cold air to enter the shop.

The air curtain itself is also causing air flow that can be felt as draft even when working properly. The same holds for revolving doors due to the rotation. In some cases air curtain parameters are not well chosen: too low mass flow and supply velocity are often observed (and sometimes also unnecessarily high). Sometimes the air curtain is not placed close enough to the entrance or only covers the entrance partly, which allows cold air to enter the shop.

Furthermore it is often not taken into account that an air curtain at the entrance is interacting with the indoor climate

- A warm air curtain is contributing to the heating. Then, sometimes people are opening windows in upper floors because they feel too warm!
- Over-pressurization can blow away the air curtain.

It was also found that wind leads to draft inside the shop even if only one entrance was present, if the entrance was situated at the corner of a building.

It was widely believed that revolving doors would provide the better solution in any case without problems. However there are also some practical problems found:

- Revolving doors without local air heating of any kind will transport beside people also cold air into the shop.
- The rotation is inducing draft in a distance of up to 4m.
- They are very rarely air tight.
- Standby rotation (without people passing by) deteriorates the inside comfort and energy performance.
- Very often a revolving door is accompanied by a standard door. Many people are using the standard door as they are afraid to use the revolving door. The shielding effect is then evidently bypassed.

4. NUMERICAL INVESTIGATIONS

The field survey made it possible to compare the importance of the many factors influencing the air flow around the entrance and its impact to the feeling of comfort.

It is however very difficult to get complete flow pictures experimentally in a shop at different situations. Also the performance of different solutions for the entrance regarding comfort and energy loss can only be compared in a real setup in a test chamber or numerically, as all the real shops are different.

Therefore a large number of numerical simulation has been made for different entrance designs with simple doors, double doors, with and without air curtains of different kinds, with tight and leaky buildings etc. The emphasis of the CFD calculations was not a determination of the direct air curtain parameters (this was done e.g. by Lam et al. [4]) but on the interaction of air curtains with other factors of large importance in buildings.

A numerical model of a reference shop ($12x25m^2$ floor area, 3m high, several storeys in some cases) was set up with different entrance configurations of always the same opening size of 1.6m width and 2.1m height. In any case an outdoor volume of at least $50x25x50m^2$ is included in the calculation domain. For the models with leaky buildings the outdoor air space extends around the building.

Much care must be taken however to ensure grid-independent solutions due to the complex air flow associated with air curtains. The numerical models consist therefore of as many as 100'000 to 200'000 cells. For the solution of the transport equations the commercial code TASCflow was used.

From these calculations mass and energy flow through the entrance were deduced for tight and

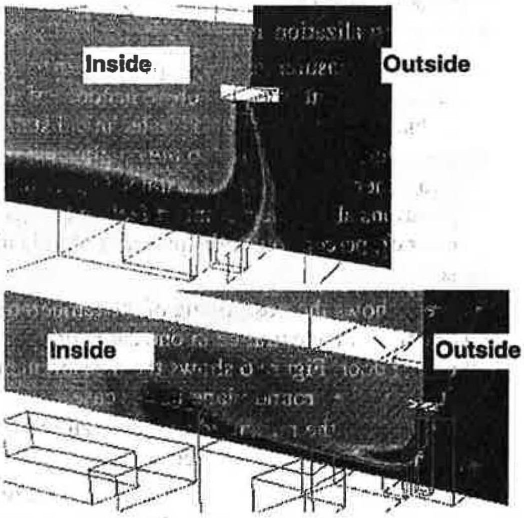

Figure 8: Above: Proper shielding by air curtain. Below: Air flow pattern when an opening to outdoor in an upper floor is opened (instant view of a transient simulation).

leaky buildings. These calculations could be extended to different wind situations if wished.

In the following, the results for some cases of particular interest are shown. All the simulations and loss values are for a temperature difference of 20K between inside and outside.

Case 1

The first case shows an entrance with an air curtain blowing vertically from above. The parameters like mass flow (3000m^3/h), velocity and exit angle are chosen such that a good shielding between inside and outside is possible (Figure 8 above). The energy loss is about 10kW as compared to 19.5 kW without air curtain.

If however the building is leaky or an opening in an upper floor is opened, then the air curtain is not reaching the floor anymore but is deflected to the inside of the shop, and cold air can enter the shop along the floor. Warm air is leaving the building through the opening in the upper storey (Figure 8 below).

In this case the energy loss is 29 kW; without air curtain the energy loss is 36kW. There is some loss reduction due to the presence of the air curtain but it is obviously not working properly.

Case 2

The second case shows an department store with over-pressure in the main floor. The supply rate is much higher than the return rate. The difference volume rate is flowing through the entrance to the outside, and the air curtain is blown right away.

Unfortunately this is not the end of the story, but cold air can still enter the shop along the floor (see Figure 9). This behavior was found in a real store and was also reproduced numerically.

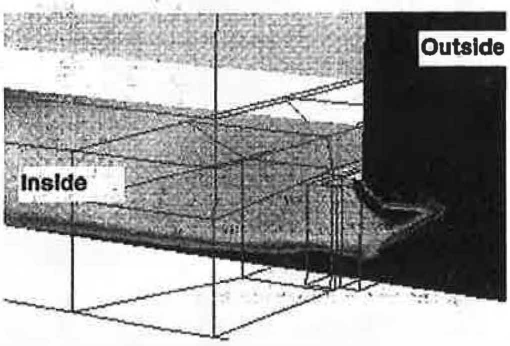

Figure 9: Over-pressurized shop with air curtain blown away.

Case 3

The third case shows an double-door entrance with an air curtain blowing horizontally from the sides. The air is blown from two vertical free columns which suck in air from the inside of the shop on the back sides of the columns. Even when the shielding of the two plane jets blowing against each other is good, cold air still can enter the room through the horizontal spacings between the columns and the inside wall of the door frame on both sides (see Figure 10).

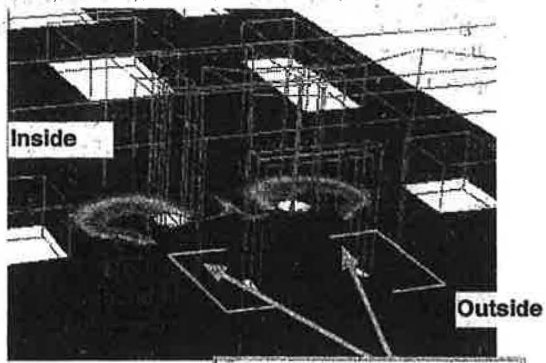

Figure 10: Wind shi **freestanding columns** *air curtain. The columns are standing free so cold air can enter the room despite the air curtain working properly.*

Case 4

This case shows an entrance with an air curtain blowing vertically from above. The air supply was mounted at a distance of 0.6m from the entrance allowing cold air to enter along the two sides (Figure 11).

Again this behavior was found in one of the field cases.

The latter two examples show clearly the importance of the geometrical arrangement beside the ventilation parameters.

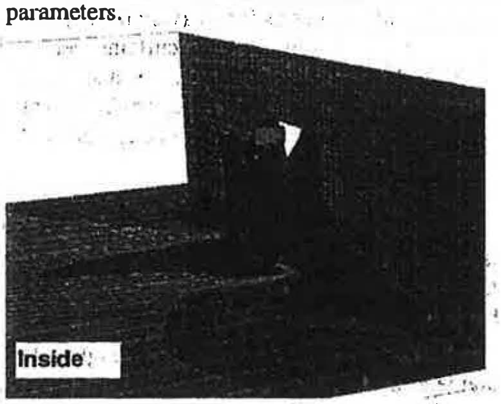

Figure 11: Vertically blowing air curtain, mounted at a distance of 0.6m to the opening area. Cold air can enter along the two sides.

Conclusions from the numerical simulations:

The simulation enables to identify the location and the strength of comfort problems (i.e. areas of draft or cold air) and to derive the energy loss from the resulting fields, even for complex situations with air curtains and leaky buildings, where simple analytical treatment is not anymore applicable.

The examples demonstrate clearly that even quite strange behavior of an air curtain can be explained by studying the numerical results.

The heat loss with well working air curtains in a tight building depends mostly on mass flow, velocity, exit angle and geometrical parameters of the air curtain allowing good and tight covering of the whole opening area.

There is no significant difference between vertically and horizontally blowing air curtains if both are covering properly the entrance opening, which depends mainly on the geometrical layout and on an initial velocity of about 5-7m/s. The heat loss of an air curtain at moderate flow rates (2000-4000m^3/h), as they can be used in quite tight buildings, is about 7-13 kW. This figure has to be compared to the loss of 19.5kW for the opening with sliding doors only (see Table 2).

The use of a wind lock without air curtain leads only to small loss reduction (from 19.5 to 18kW) when all the doors are open. The advantage of the wind lock is its better performance at low user frequencies if at least one door is closed.

5. ENERGY LOSS

It is quite interesting to compare the energy losses associated with different solutions for the entrance situation.

The values used here are derived from various sources. The energy losses with free openings are taken from the analytical formulae. These values agree well with those from CFD and with experimental values as far as available [5]. The loss values in combination with air curtains were derived from the CFD calculation, but agree also well with experimental values [internal reports]. The values for revolving doors are derived from experimental values [internal reports].

Table 2 and Figure 12 show data for a tight building, Table 3 and Figure 13 for a leaky building. The leak is an opening of 1.4m^2 at a height of 20m. All the loss values are for a temperature difference of 20K between inside and outside.

The entrance width is 1.6m and the height 2.1m. The diameter of the revolving doors is larger, the transfer capacity for people is however smaller than for the normal entrance.

The basic values are those for full load, i.e. the moving doors are always open, i.e. for very high person frequencies. It makes sense from the energy and comfort point of view to let the moving doors close when not used. For this case values have been derived for the energy loss at a single person's passage.

These values are based on an estimated effective opening time. For a single sliding door for example,

	Width of passage	Loss rate Full load		Single person Time	Heat loss	
	m	kW	%	s	kJ	%
Autom. sliding door (ASD)	1.6	19.5	100	4	78	100
Rev. door (4.2m, 4 segments)	1.6	13	67	—	150	192
Rev. door (4.75m, 2 segments	2.4	17	87	—	350	449
Wind lock with 2 ASD	1.6	18	92	2.5	45	58
AC horizontal, +14K, ASD	1.6	13	67	4	52	67
AC vertical, +7K, ASD	1.6	10	51	4	40	51
AC vertical, cold, ASD	1.6	7	36	4	28	36

Table 2: Comparison of energy loss for tight building, reference entrance shaded.

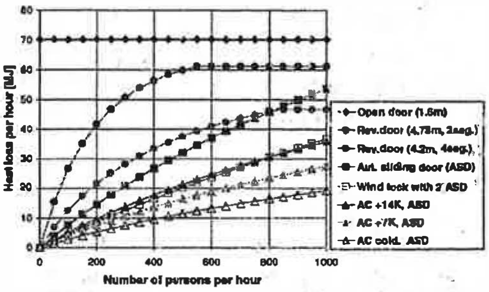

Figure 12: Energy loss vs. user frequency for tight building.

7s are passing by from the beginning of the opening process until the moving doors are closed again. The effective time during which the fully developed flow is established through this opening, is estimated to 4s. in the case of 2 consecutive doors this time is significantly smaller; a value of 2.5s was assumed. For a revolving door, the air exchange of almost one full segment was assumed as the loss for one person's passage.

The energy loss for a high number of people is not simply a linear function, but the rate of increase is successively decreasing until the curves finally approach asymptotically the steady-state values of the fully open cases, due to the increasingly simultaneous passages of some people.

	Width of passage	Loss rate Full load		Single person Time	Heat loss	
	m	kW	%	s	kJ	%
Autom. sliding door (ASD)	1.6	100	100	4	400	100
Rev. door (4.2m, 4 segments)	1.6	15	15	—	170	43
Rev. door (4.75m, 2 segments	2.4	19	19	—	390	98
Wind lock with 2 ASD	1.6	95	95	2.5	239	59
AC horizontal, +14K, ASD	1.6	85	85	4	340	85
AC vertical, +7K, ASD	1.6	85	85	4	340	85
AC vertical, cold, ASD	1.6	85	85	4	340	85

Table 3: Comparison of energy loss for leaky building, reference entrance shaded.

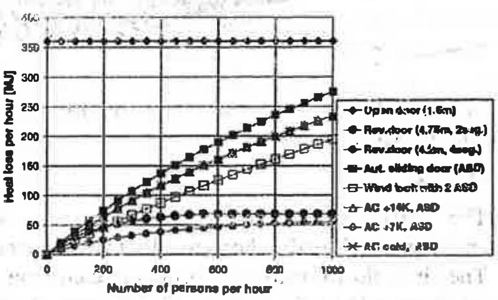

Figure 13: Energy loss vs. user frequency for leaky building..

For the 3 classes of entrances, "single opening" (with any kind of air curtain), "two consecutive doors" and "revolving door", three different functions describing the estimated simultaneousness have been used.

Figure 12 shows the loss values as a function of the customer frequency. The cases with air curtains show much smaller losses than with revolving doors for low person frequencies. For a leaky building this picture changes dramatically (see Table 3 and Figure 13). The big advantage of the revolving door is theoretically complete separation of the inside and outside space. The energy loss is basically unaffected by the leaks in the building. Here some additional loss was assumed due to some leaks in the revolving door itself. In all the other solutions the energy loss is in the range of 80-100kW. In a leaky building, the revolving door is the best solution from the point of view of energy loss.

In practice it is important to take care of the cold air which is entering the inside space when the revolving door is used. An air curtain attached to the revolving door makes sense if there are working places near the entrance.

5. CONCLUSIONS

There are conclusions at several levels that can be drawn from this study.

The agreement of the CFD results with available data demonstrate the ability to deal with these types of cases if sufficient care is taken.

From the study as a whole, the following items have been identified as the key factors for the design of an entrance obeying basic comfort and energy requirements:

- Building tightness
- Combination with other entrances
- Correspondence with building ventilation system
- Position of entrance (low wind exposition)
- Entrance size (as small as possible in winter, particularly as low as possible)
- Doors which are tightly closed when not used
- Additional equipment (revolving door, air curtain) that is well designed and is made sure to work properly

Several consequences from these keywords are discussed in the field investigation chapter.

Every entrance is associated in the cold season with problems regarding draft and cold air which are enhanced in a building with several openings at different height levels and the presence of wind.

Recommendations for the designer

Mechanical solutions like wind shields or revolving doors may reduce the draft problems. For a satisfactory comfort situation near the entrance, a combination with some local heating is necessary.

Tight building:

At low person frequencies, a wind shield with two consecutive automatic doors is a big improvement compared to the simple entrance, if the closing mechanism is optimized (i.e. closing fast).

At high frequencies air curtains may provide good comfort conditions when optimally designed.

It must be realized however that also air curtains induce strong air currents that can be felt as far as 10m or more. Therefore the supply temperature must be ensured to be high enough in order that high air velocities are not accompanied by low temperatures.

It is also important to consider the interaction with the standard ventilation system of the building as a net flow through the opening will influence the performance of the air curtain, and the local heating of the air curtain can contribute substantial heating to the shop.

Leaky building:

In a very leaky building or in building where some entrances are strongly exposed to wind influence, the only efficient means for good comfort inside is a revolving door. The door must be very tight however, and a combination with local heating is strongly recommended. This can be achieved by warm air supply within the revolving door, or an air curtain attached closely to the door frame on the inside of the building.

If the described solutions cannot be realized, working places have to be moved away from the entrance or they have to be protected against draft and/or equipped with additional local heating.

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