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Application of Air Flow Models to Aircraft Hangars with Very Large Openings

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Synopsis

In line maintenance hangars, air planes stay about 2 hours, usually at night-time. The cooling-down of the inside air during the opening time of the hangar gates (up to 5 times per night, lasting 15 to 30 minutes each) has a considerable impact on the comfort conditions for the workers, and on the energy required for reheating.

The time-dependent air flow rates and associated heat loss rates during the door opening and closing cycles is assessed by simple transient thermal models and CFD (Computational Fluid Dynamics) calculations. The results obtained by these models agree well with the experimental data of the transient temperature response during the opening and closing of the door of a real full-scale hangar.

The effect of using huge air curtains (up to a height of 20 m, a width of 80 m, and moving air volumes at rates of 400 m^3/s) to prevent heat loss was studied numerically by CFD in two- and three-dimensional models for time-dependent conditions. The study covers also transient effects when an aircraft is actually crossing the air curtain, and shows the feasibility of assessing the energy saving potential of such air curtains using CFD.

1. Introduction

In line maintenance hangars for small repairs, air planes stay about 2 hours, usually at night-time. Such hangars can hold several planes, so 5 door openings lasting up to half an hour each occur frequently. The cooling-down of the inside air during the opening time of the hangar gates has a considerable impact on the comfort conditions for the workers, and on the energy required for reheating

In order to assess the energy loss during the opening time, measurements have been carried out in a real full-size hangar by Sulzer Energy Consulting, Winterthur, Switzerland. The time-dependent air flow rates and associated heat loss rates during the door opening and closing cycles is assessed by simple transient thermal models and CFD (Computational Fluid Dynamics) calculations, and compared to the available measurement data.

Therefore the possibility of installing a huge air curtain across the hall hangar opening (full-width, about 80 m long and 20 m high) was investigated by a computational fluid dynamics (CFD) simulation within a project request intitiated by Swissair Real-Estate, Zurich Airport, Switzerland.

Some of the modeling techniques have been developed already earlier for the modeling of bidirectional air flow through open windows and doors [Schälin et al. 1992], where "large" has been used for openings of the order 1-3 m, as opposed to the width of cracks. In this paper "very large" is used for door sizes of the order 15-30 m.

This paper reports some of the most interesting measurement results and comparisons with different models for the air flow in a hangar through the open door, plus some results for different configurations of an air curtain.

Several studies of the dynamics of gravitational flows occurring during door opening can be found in the literature [Linden and Simpson, 1985; Kiel and Wilson 1986]. However these studies were concerned with the adiabatic case where heat transfer is not playing a role. By combining a single zone thermal model with the gravitational flow model, [Van der Maas and Roulet, 1989; 1990] were successful in predicting the dynamic energy losses through open doors and windows. A extension of this cooling model to several zones ventilated in series [Van der Maas and Roulet, 1993] was shown to be able to estimate the temperature stratification after opening a window or door for the case of single-sided ventilation.

2. Measurements in an Aircraft Hangar

Measurements in a hangar have been performed by Sulzer Energy Consulting, Winterthur, Switzerland. The aim of the measurements was to investigate the cooling-out of the hangar during the opening-time when an airplane enters or leaves the hangar. An important design issue, motivating the measurments is the temperature recovery time after closing of the door, in relation with the type of heating system (floor heating or air heating systems). The issue is crucial for the design of hangars with frequent opening times (several times an hour) related to the short maintenance periods of modern aircraft. The problem is characterized by time-dependent flow and time dependent boundary conditions whereas static concepts as the U-value of the envelope are of no use when describing the indoor temperature variation with time.

2.1. Hangar description and measurement set-up

The investigated hangar is 150m wide, 90m in depth and the distance from floor to roof is 33m. The rolling doors comprise 8 segments, 18 m wide and 27m high. The roof is well insulated with a U-value better than 0.4. The 13'500m^2 concrete floor slab contains floor heating pipes at a depth of 15cm.

The floor heating system has a power of 1.7MW, which corresponds to 130W/m^2. The space setpoint temperature for the floor heating system is 18°C, with a maximum surface temperature of 26°C. Twenty auxiliary hot air blowing systems are installed above the doors and along the walls with a total power of 3.3MW.

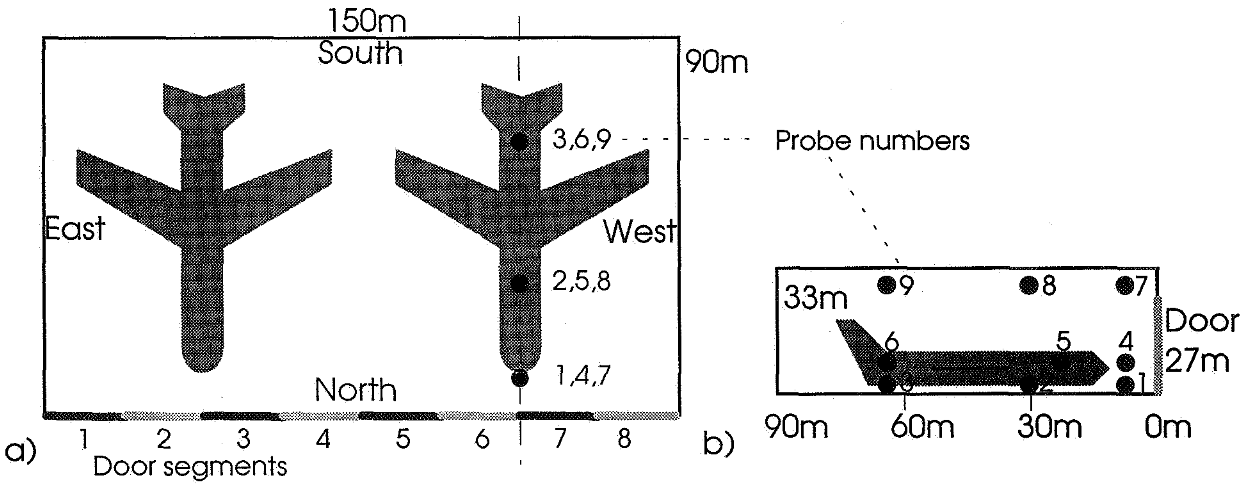


Figure 1. Measurement positions in the 90x150x33m hangar. a) top view with cross section of Figure b) indicated. b) cross section between door segments 6 and 7.

Figure 1 shows the configuration of the hangar and the temperature measurement positions. Small temperature loggers were installed using as a support the maintenance structure around the airplane. Data were logged every 10s before and during the door opening, and during and after the door closing. In a plane normal to the door plane, 9 temperature measurement points have been chosen (see also Table 1)

-3 near to the floor : 1-front, 2-middle, 3-back

-3 in the middle : 4-front, 5-middle, 6-back

-3 just above the top of the door level : 7-front, 8-middle, 9-back

The probes 2 and 5 were mounted on the maintenance structure around the plane and only probes 1 and 4 are fully exposed to the cold air gravity current. Probes 3 and 6 were placed at the back of the plane external from the structure.

Of the three data series which are available, one has been chosen for presentation. The data concern the measurements during a winter night, where two door segments were opened (maximum opening width 37m).

Probe	Placement	distance from door	height above floor
1	bottom door	10	0.5
2	bottom center	32	0.3
3	bottom back	64	0.3
4	center door	9	5
5	center center	19	7
6	center back	63	5
7	top door	6	30
8	top center	29	30
9	top back	66	30

Table 1: Measurement probe positions (see also Figure 1).

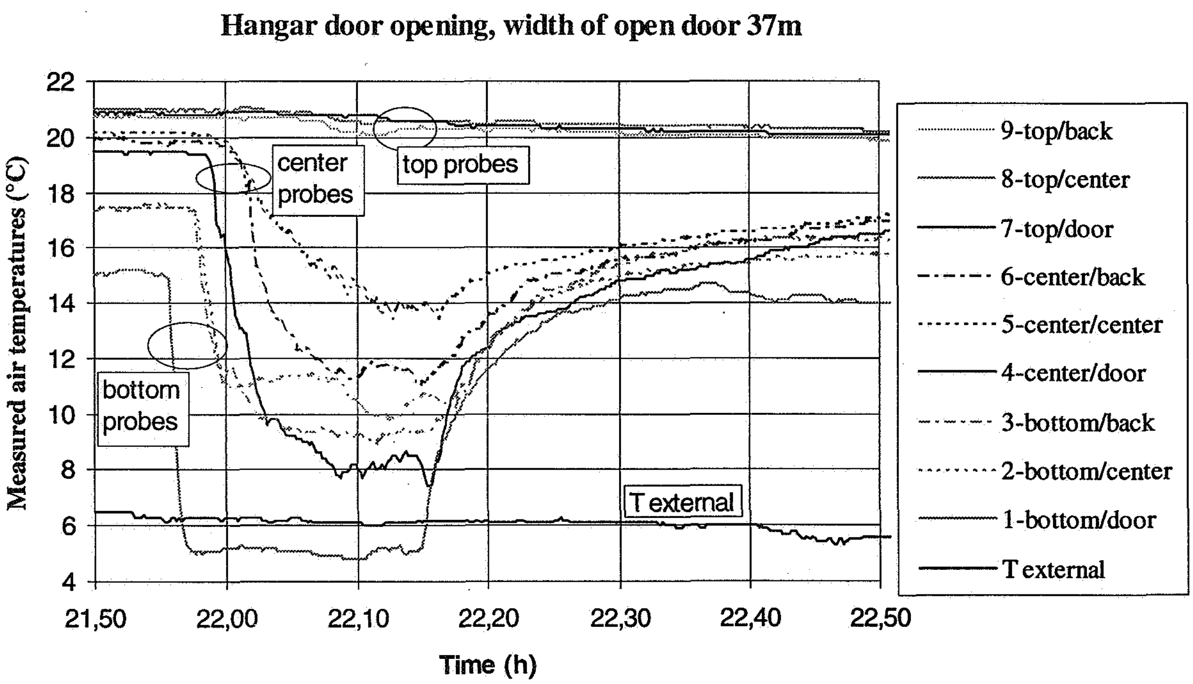


Figure 2. The measured air temperatures at nine positions in a center plane normal to the hangar door opening (Table 1, probes 1 to 9) during the opening and closing of 2 hangar door segments (door opening 2 in Table 2).

2.2. Experimental results

In Figure 2, the temperatures of probes 1 to 9 are given during and after the door opening. It took about 5 minutes for the doors to roll aside, and during this opening phase the temperatures at floor and middle level dropped rapidly, while above the top of the door the temperatures did not change remaining nearly constant at 20.5°C. During the closing phase of about 6 minutes, a rapid temperature rise near floor is observed.

The following can be observed on Figure 2. Probe 1 is coolest and drops to 5°C, which is two degrees below the outdoor temperature. From this it can be concluded that the measurement of the outdoor air temperature is not correct; indeed afterwards it was concluded that this probe was mounted too close to the structure of the building. Probes 2 and 3 are shown to have a delay of 2.5min, and are 5 to 6K higher in temperature than Probe 1. Probe 4 (middle door) is delayed by 3.5min. and is 1K colder than probe 2. Probe 5 (middle middle) is delayed by 6min and is 6K warmer than the middle door. This probe was mounted on the maintenance structure and was not directly exposed to the cold air current. Probe 6 (the middle back) is delayed by 6min and 2K warmer than Probe 4. During temperature recovery, the probes remain colder than before opening by about 2K. The top probes, steady decrease with outdoor temperature, but not influenced by door opening.

3. Application of Thermal Zonal Models

The model described in [Van der Maas and Roulet 1993], applies when a single air flow path can be defined. A partial validation of the model with details of the used algorithms can be found in this reference. The principle of the model is to couple for each zone airflow and heat transfer by requiring a heat balance and conservation of mass. The definition of a single air flow path implies that the zones must be placed in series of one another.

In Figure 2, the multizone cooling model is given schematically for three zones. The algorithm for the cooling model includes a recurrence relation which allows to calculate the air temperature in the last zone, from knowledge of the inlet temperature of the first zone. The ventilation flow rate is the same for all zones and depends on these air temperatures. A few iterations are sufficient to obtain the air temperatures for which the heat balance is satisfied for all the zones. The input parameters for each zone are: (i) the heat transfer surface area and the heat transfer coefficient, (ii) a material parameter characterizing the dynamic thermal response of the surface temperature, called thermal effusivity, and (iii) the initial wall surface temperature.

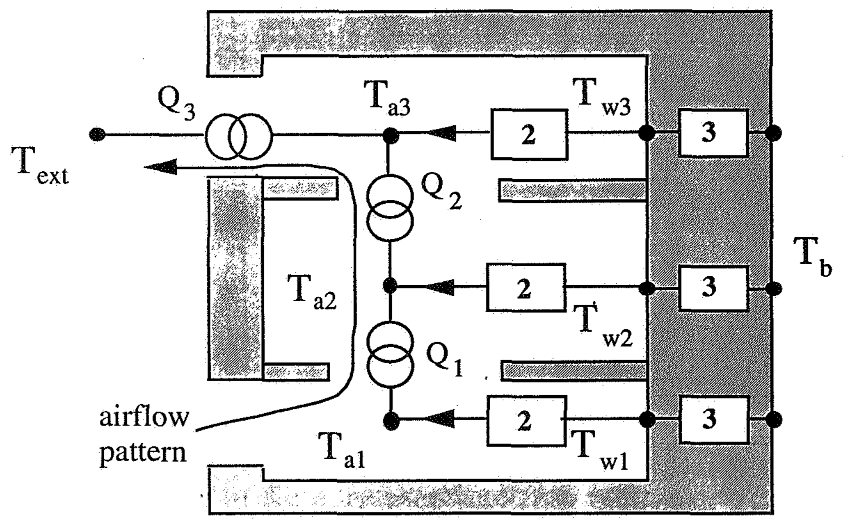


Figure 3. Multi zone cooling model with three zones. (2) are the heat transfer resistances and (3) is the dynamic wall resistance. The heat sources Q_i, represent the combined effect of internal heat gain and ventilation heat loss. For each zone the principles of mass and energy conservation apply assuming that in the dynamic regime the zones are only coupled through the air temperature nodes.

The (time dependent) output parameters for each zone are calculated from the external air temperature variation and are: (i) the air temperature, (ii) the surface temperature, and (iii) the ventilative cooling load.

The airflow pattern without wind is quite well defined by the nature of the gravity wave. After opening the door, the gravity current enters, flattens and spreads out over the floor and flows to the back, where it is relected back and the hangar starts to fill up with cold air (warm air is escaping through the top of the door) like a displacement ventilation system. This is confirmed from the delays with which the several probes react to the cold air entering the hangar (see Figure 2). First probe 1, near the door; then the other bottom probes, next the second layer probes. Unfortunately there are no temperature readings between heights 5 and 27m, so that the dynamics cannot be followed in detail.

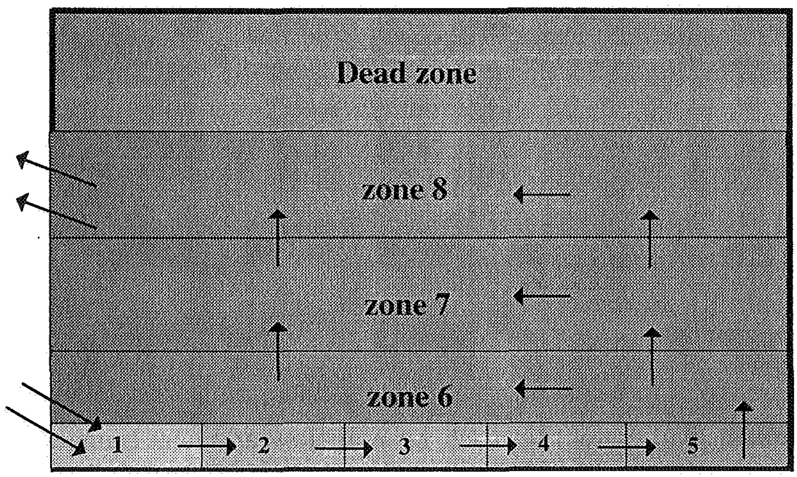


Figure 4. The 8-zone geometry representing the gravity current air flow pattern with open hangar door.

The zones have been defined following this gravity current air flow pattern (Table 1, Figure 3). The height of the first zones should correspond ideally to the height of the gravity wave. The height is half the door height close to the door, but when it spreads out over the floor, it flattens [Lane-Serff et al. 1987]. From Figure 2 it can be seen that Probe 4 which is close to the door senses the cold wave a full two minutes later than the lower probe 1. Because of the positioning of the measurement probes, the zones in contact with the floor were taken to be three meter high and included probes 1, 2 and 3. Zone 6 reaches from 3 to 5m, including probes 4, 5 and 6.

Because the flow pattern is only approximately described by these zones, the choice of the zones is not unique.

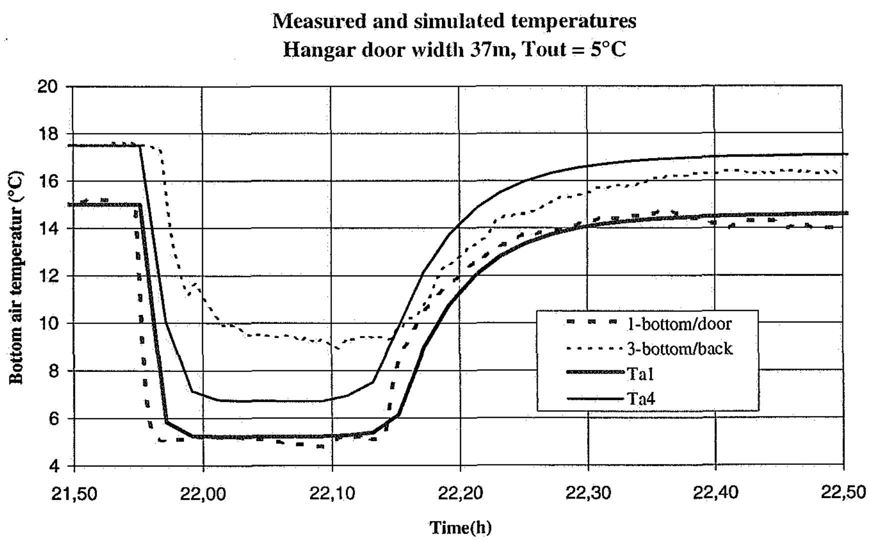


Figure 5. Comparison between measured and simulated air temperatures in zone 1 (bottom door, Ta1) and zone 4 (bottom back and Ta4).

In Figure 5, the predicted temperatures of zones 1 and 4 have been compared with the measured temperatures of probes 1 and 3. It is seen that near to the door and to the floor, the temperature falls rapidly to close to the outdoor temperature. The probe 3 temperature is higher than this simple model predicts. (It is difficult to understand how important the role is of the structure surrounding the airplane).

It is interesting to consider the effect of the opening width on the cooling. Indeed the heat loss rate is expected to be proportional with the opening width. In Figure 6, the mean temperature at ground level was calculated for three doorwidths. It is seen that a reduction of the door width from 37 to 5m width, is not sufficient to avoid a substantial lowering in air tempeature. This implies that even when the heat loss rate is reduced by more than a factor 7, the indoor temperature continues to drop substantially.

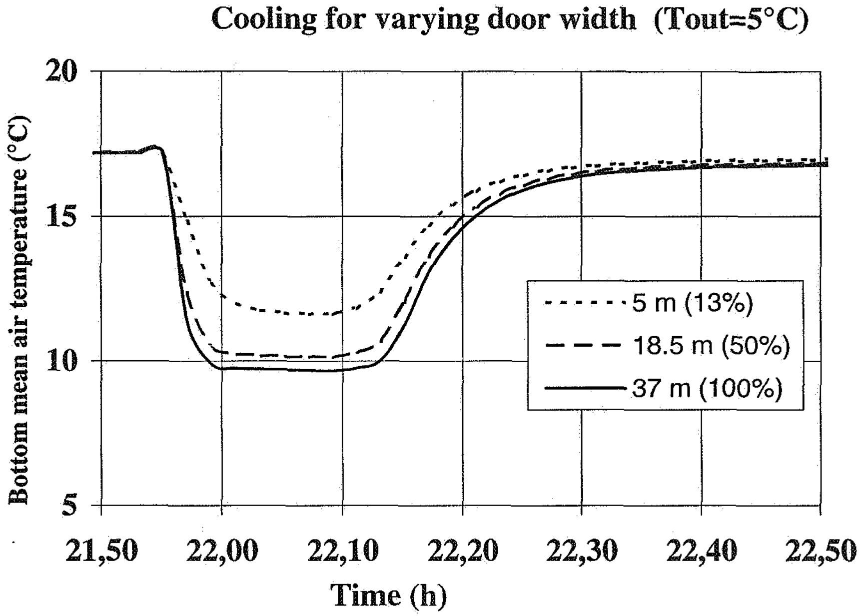


Figure 6. The simulated air temperature averaged over zones 1 to 5, for different opening widths. A 5m wide door opening still causes substantial cooling.

This effect is related to an important factor in the model described in Figure 3, which is the ratio between the heat transfer resistance between the air and the wall, and the equivalent ventilation resistance of the door. As long as the ventilation resistance is relatively small, the indoor temperature will drop to close the outdoor temperature.

Discussion of energy losses. It can be concluded that the overall features of the cooling of the hangar are reproduced. It appears that the energy losses during the opening are mainly due to the replacement of warm indoor air by cold outdoor air, the cooling of the floor and structure is relatively small.

Without air curtain, the heat loss rate as a function of opening time decreases rapidly : once the warm air (T_2) has been replaced by colder air (T_1) the heat loss rate by convection is considerably reduced, the residual heat loss being governed by the cooling of the wall surfaces.

In the extreme case of adiabatic walls, the energy loss stops after a few minutes and equals $E=(T_2-T_1)\rho\ Cp\ V$. The recovery time is shortened when the wall surface temperature remains high (massive surfaces). However the heating power which can be provided by the warm wall surfaces is limited. To reduce the recovery time hot air blowing systems can be used with advantage. Hot air blowers have a low inertia and can function efficiently for short periods of time. Because hot air rises, the warm air should be distributed at ground level which means that the hot air should be blown downward and reach the floor.

The heating power Φ, can be calculated as a function of desired recovery time τ_R :

$$\Phi\ \tau_R = E \qquad \text{or} \qquad \Phi = (T_2-T_1)\ \rho\ Cp\ V/\tau_R \tag{1}$$

For a volume of 364'000 m^3, the power in MW and a recovery time of 5 min this estimate yields: $\Phi = 1.5\ (T_2-T_1)$ MW. For a fixed hot air heating system of 10 MW for example, the recovery time depends on the difference between the outdoor temperature and the desired indoor temperature :

$$\tau_R\ (\text{min}) = (T_2-T_1)\ \rho\ Cp\ V/\ \Phi/60 = 0.7\ (T_2-T_1) \qquad (2)$$

and to increase the temperature by 10K would require 7 minutes or a burst of energy totalling about 1000kWh.

4. CFD Calculations for an Aircraft Hangar

The CFD calculations have been performed using the commercial code FLOVENT, a CFD program designed for ventilation purposes. It can be used for simple cartesian grid systems and is based on the SIMPLE algorithm [e.g. Patankar 1980]. The standard k-ε-turbulence model is included. Following quite different situations have been studied:

- Investigation of mass flow through door and air flow pattern inside a hangar, when a hangar door is opened suddenly: transient 2-dimensional simulation.
- Parameter study for air curtain in the door plane to prevent heat loss during door opening: steady-state 2-dimensional simulation.
- Preliminary heat loss study for air curtain: transient 2-dimensional simulation.
- Detailed heat loss study: transient 3-dimensional simulation.

4.1 Hangar with free flow through open door

In a previous study [Schälin et al. 1992] the bidirectional air flow through a large opening (a normal door of a height of 2.2 m) in a room, which is closed apart from the door and not ventilated, was investigated in some details. The velocity profiles obtained by CFD show good agreement with experimental data and prove the ability of the CFD modeling technique for this flow type at this moderate height.

In this study the CFD modeling technique was applied to very large openings. In order to save computation time, the hangar as described in section 2.1 was modeled in two dimensions only (see Figure 7). Boundary and initial conditions were taken as much from the experimental values as possible. Initial conditions assumed were 20°C inside the hangar and 5°C outside. These conditions and the resulting velocity and temperature distribution are not known in sufficient details; therefore it cannot be expected that the curves in Figure 2 could be represented in full detail and an expensive three-dimensional calculation was not carried out. The main purpose of this study was the demonstration of the ability to predict the main flow features by CFD. The size of the grid used was 57x42 cells; it is shown partly in Figure 9.

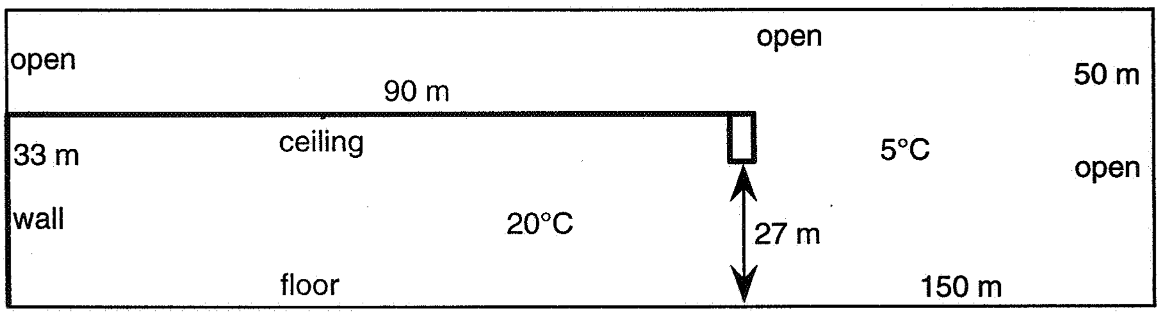


Figure 7: Geometry used for two-dimensional air flow simulation in the hangar described in section 2.1.

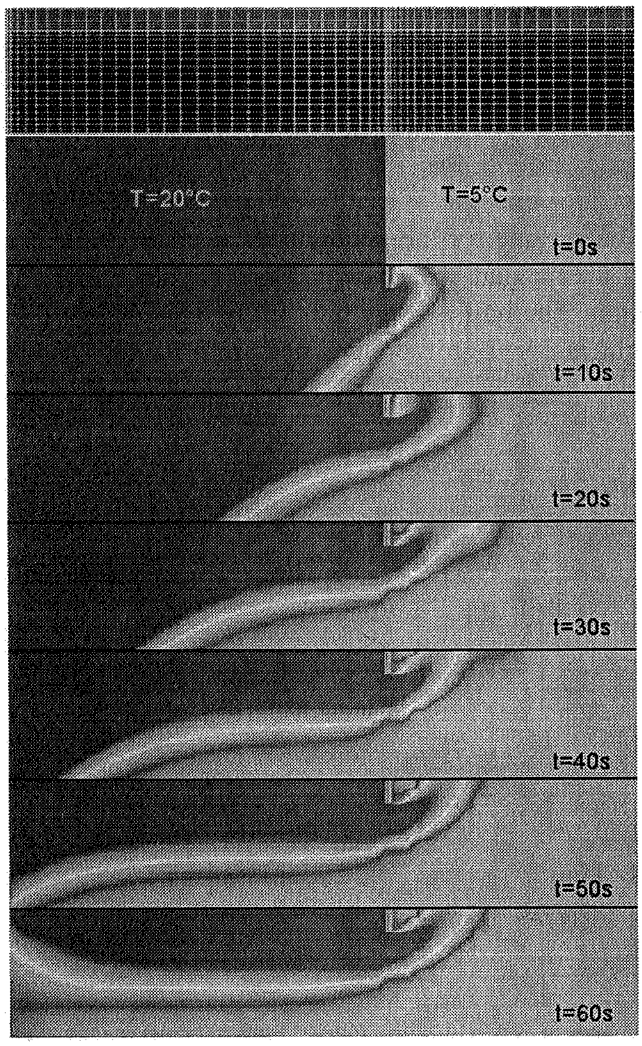
At the beginning of the calculation time (t=0) the door was suddenly removed and a bidirectional flow starts to establish through the door. Figure 8 shows the temperature distribution at several instances in the first 60 s. It can be seen quite easily that after 60 s the cold air has reached the end of the hangar along the floor. After that the cold air starts to empty the hangar from the back; the behaviour is like a gravity wave which is reflected at the back wall.

The velocities in the door plane are in the beginning about 1.5 m/s near the floor and 2.5 m/s near the top of the door, and will fall to 0.6 m/s after 3 minutes (200 s) and to about 0.2 m/s after 10 minutes (600 s). The observed velocities in a real hangar are of the same order, but no measurement values are available. A calculation for the maximum velocity in the beginning,

$$v_{max} = C_d \sqrt{\frac{g H \left(T_a - T_{ext}\right)}{T_{ext}}} \tag{3}$$

and C_d=0.63 [Van der Maas et al. 1989], gives 2.4 m/s in very good agreement.

After about 5 minutes most warm air in the hangar has been replaced by cold air, except for that part near the ceiling which is at a larger height than the door height (i.e. above 27 m). That air part remains unaffected for a longer time (see Figure 2, experimental results). Figure 9 shows the temperature distribution in the hangar after a calculation time of 20 minutes (1200 s). This feature (stagnant warm air in the upper part of the hangar) cannot be obtained by using the k-ε-turbulence model, as that model assumes a fully turbulent flow which is not the case in the upper part of the hangar. Without low-Reynolds-number corrections, it will overpredict the amount of turbulence in those stiller parts [Chikamoto et al. 1992] of the flow which leads to a higher mixing and a total sweep-out of warm air even in these higher parts. As it is not possible to include user-defined model corrections in the CFD program used, the results in Figure 8 have been obtained in a laminar calculation; the flow characteristics in the beginning are similar to those obtained by using the k-ε-turbulence model.



The described feature can be seen in the experimental curve in Figure 2, where the bottom position probes show a fast decrease in temperature, the probes at the medium level exhibit a slower decrease and the top probes at a height of 30 m remain unaffected by the door opening. The probes at a height of about 5 m (probes 4-6) show a delayed temperature decrease by 1 minute; this feature cannot be seen in the CFD calculation because in the measurement situation the air flow is entering a door which is open only one quarter of the hangar width; the cold air flow distributes at decreasing height.

Figure 8 (left): Time sequence of temperature distribution after opening of hangar door.

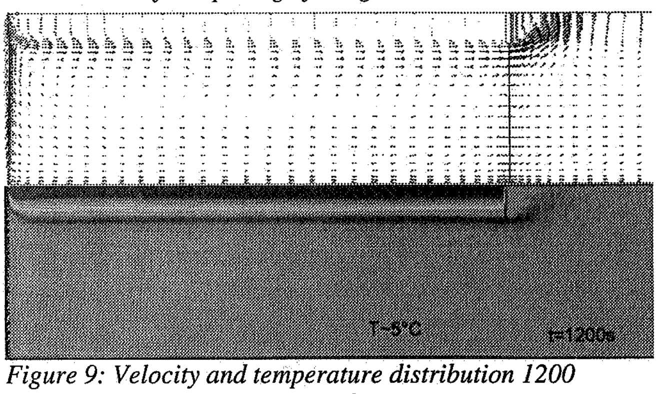


Figure 9: Velocity and temperature distribution 1200 s (20 min.) after opening of the door.

The spreading out of the 2D gravity wave and the lowering of its height with the distance from the door was observed and explained briefly in [Linden and Simpson, 1985; Lane-Serff et al. 1987].

Figure 10 shows the velocity profile across the door height after 30 s. The neutral level is slightly above mid-height, and higher velocites are found near the top of the door. The profiles are not parabolic due to the viscous forces which are not taken into account by the simple Bernoulli theory (Equation 1). [Wilson and Kiel, 1990] discuss the shearing at the neutral level (zero velocity, at about mid-hight) and the mixing of counterflows, which modifies the velocity profile from pure parabolic.

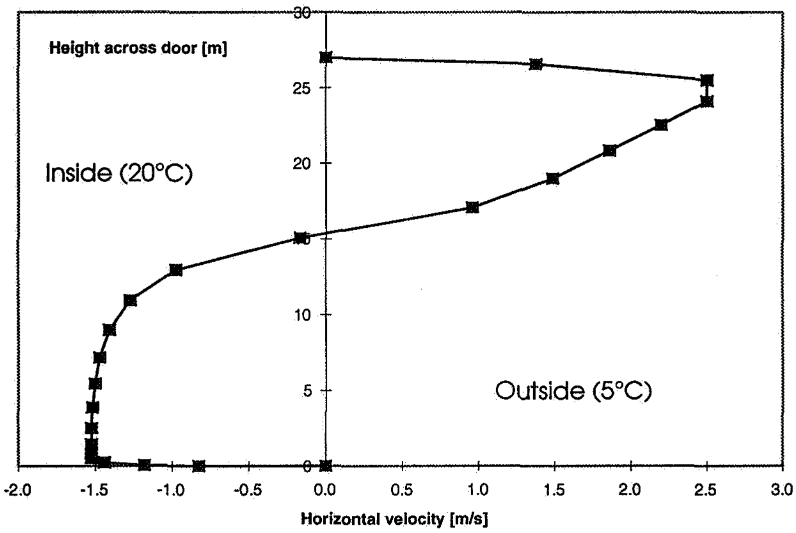


Figure 10. Velocity profile across door height after 30 s.

4.2 Hangar with air curtain

In a student's diploma thesis several questions around the feasibility and energy savings effectivity of an air curtain for the whole hangar door opening of a planned new Swissair hangar were investigated. The CFD calculations have been done for the geometrical dimensions of the projected hangar. Figure 11 shows the layout of the hangar. The dimensions are 90 m x 110 m x 22 m; the central part of the hangar is 31 m high. The hall is large enough to hold 4 medium-size planes or a very large one. The door height is 14 m on the sides and 22 m in the central part, and the total width 83.8 m.

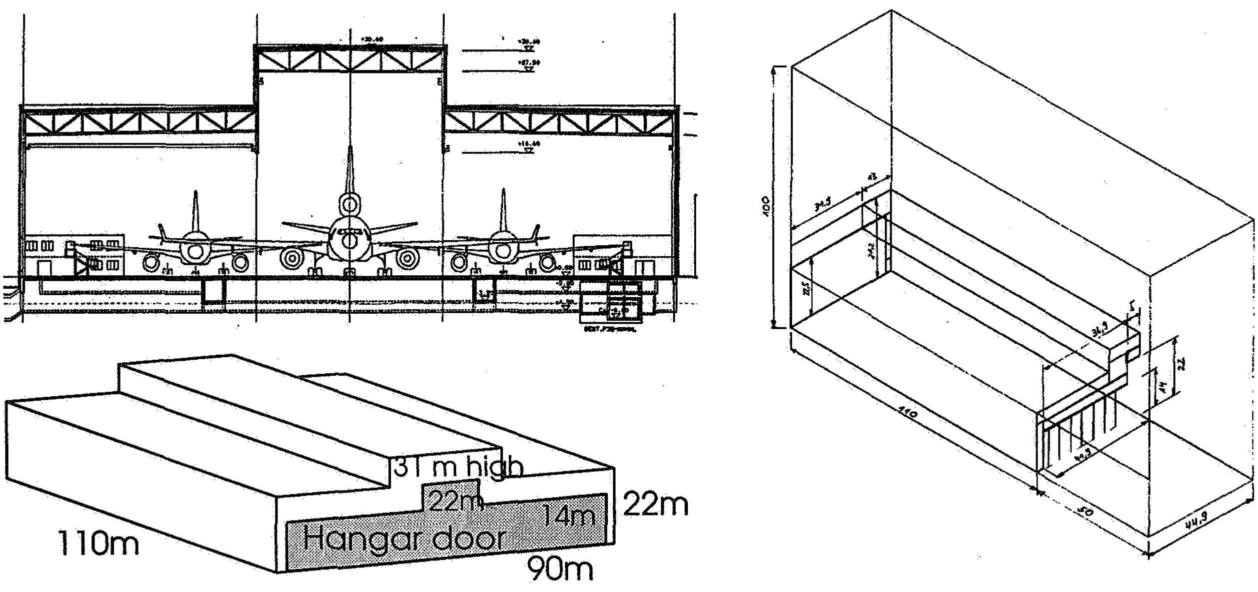


Figure 11: Projected new Swissair hangar. Top: front view with air planes. Below: sketch in perspectiv view. Right: Model for 3-dimensional calculation.

4.2.1 Parameter variation for stable air curtain

A large parameter variation was done in 2-dimensional steady-state calculations to find out favourable conditions for a stable air curtain. Out of different possible jet configurations like blowing from above and sucking from below, a quite simple jet blowing from above was chosen in order to avoid complicated installation work. Such a simple jet would be also suited to be installed in an existing hangar. The jet was assumed to be a plane jet along the whole door width (as opposed to an array of single jets). Figure 12 shows the data used for this study.

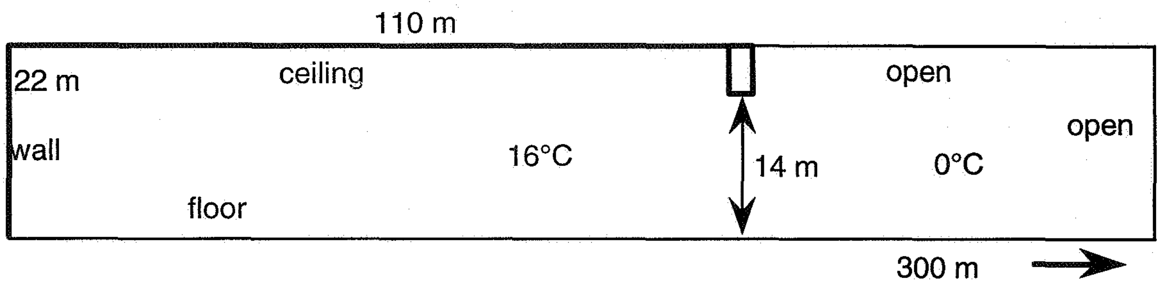


Figure 12: Geometry used for the 2-dimensional calculation for the Swissair hangar project.

Varied parameters were: jet angle (-15°, 0°, 15° to the vertical direction), jet width (0.1 m, 0.3 m), air velocity (5 to 20 m/s), jet heating (ΔT=0 to 2.5 K, if air is taken from inside, ΔT=0, 10 K, if air is taken from outside), presence of wind (0, 3, 6 m/s). The outside temperature was always assumed to be 0°C, and the inside design condition was around 16°C. It is not possible to report on all these cases, but as a main result, the optimum condition in the presence of wind was found to be in the range of: jet angle 15° towards outside, jet velocities around 10-15 m/s, and a width of 0.3 m. For a velocity of 14 m/s, a width of 0.3 m and a length of 83.8 m, the volume flow rate equals 352 m^3/s, and the mass flow rate about 410 kg/s, using a density of 1.17 kg/m^3.

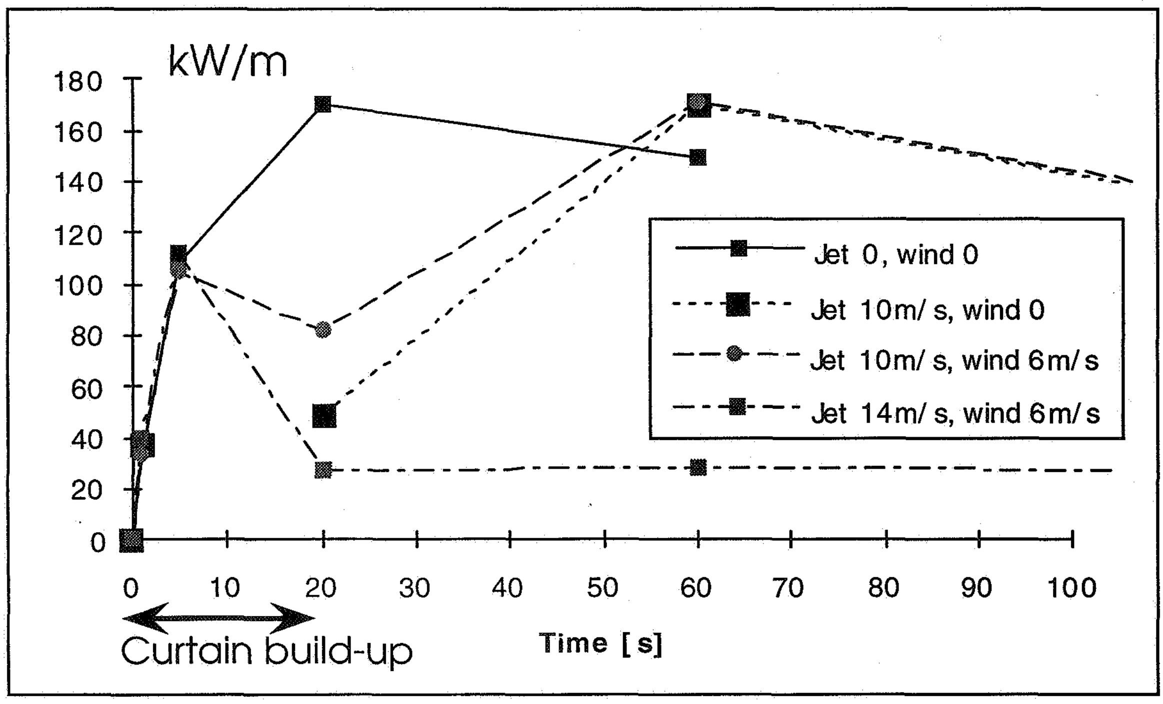


Figure 13: Heat loss in kW/m (per m of open hangar door width) for different combinations of air curtain velocities and wind speed. The curtain build-up time applies only to the 3 cases with air curtain.

4.2.2 Heat loss investigation in 2 dimensions

Preliminary energy loss calculations were done for the optimum jet configuration. In the transient CFD study the starting condition was 16°C inside and 0°C outside. At t=0 the door is open and the jet starts blowing. In this study it takes some time until the air curtain is established. The strong loss during the first 20 s can be avoided by turning on the fans earlier before the door opening.

For a velocity of 14 m/s the build-up time of the air curtain is about 20 s, much better than for a velocity of 10 m/s with a build-up time of 60 s. In the case of a jet of 14 m/s, also a better shielding between inside and outside is achieved. The inside temperature after 5 min is still around 14°C. Velocities inside the hangar along the floor are around 2 m/s.

Figure 13 shows the heat loss in kW/m through the door plane for different jet configurations, the best performance being achieved for the 15 m/s jet. The peak loss for the whole hangar width would be about 14 MW, assuming that the door would be suddenly opened completely. The power effort for the jet across the hall hangar is much smaller than the heat loss reduction; the kinetic energy of the air is about $mv^2/2$=410 kg/s * $14^2/2$ m^2/s^2 = 40 kW, and the electric power consumption of the fans would be 60 kW at a fan efficiency of about 0.7.

However these 2-dimensional calculations can only be considered as preliminary, as effects related to the real door opening process are not contained.

4.2.3 Heat loss investigation in 3 dimensions

Therefore a 3-dimensional calculation was set up for a hangar. The calculation was done for just half the hangar; a symmetry plane was assumed in the middle, see Figure 11. The size of the grid used was 50x33x23 = 37950 cells.

The calculations were performed in the presence of a wind of 6 m/s at frontal incidence for a hangar which is air-tight apart from the open front door. The door was opened step by step until it was totally open (full width of 83.8 m) after 1 minute. In the second minute of the transient calculation an air plane of the dimensions of an Airbus A320 was moved successively into the hangar. The times were chosen that short in order to save computation time. Observations in a real hangar have shown, that these times are realistic, but they represent an ideal case of optimum timing. In real practice, hangar doors stay open 10-20 minutes or more to let an airplane in or out. Consequently losses will be larger.

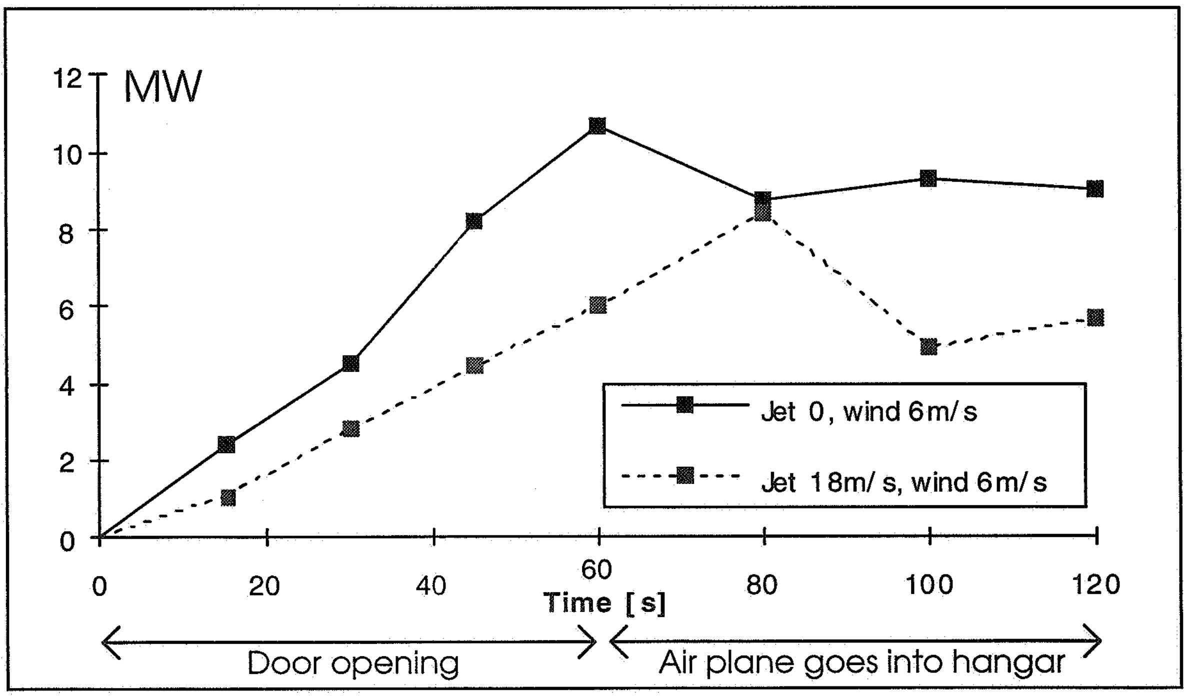


Figure 14: Heat loss rate during opening of hangar and pulling in the air plane into the hangar, obtained by numerical calculation of 3-dimensional cases, one with and one without air curtain. The MW values are for the whole hangar with full door width.

Figure 14 shows the total heat loss through the door plane with an air curtain, in comparison with a case without curtain. As the door opens linearly during the first 60 s until it is totally open, the loss also increases linearly in time. The jet used was at a somewhat higher velocity of 18 m/s than in the 2-dimensional case, as the door height in the center is also higher (22m instead of 14m).

The result shows a energy loss lower by about 40%, as compared to the case without air curtain (integrals of curves in Figure 14). In reality, this loss is even lower because the air curtain can be turned on when the door is still closed, but no more detailed calculations have been done yet. The loss is comparable in size with what is reported in the air curtain literature.

In these studies the influence of the low air plane temperature (it can be considerably below 0°C after a flight) and the radiative cooling has not been considered. It is more important when considering the overall heating power but less important when comparing situations with and without air curtain.

Figure 15 shows the temperature distribution in the door plane when the air plane of the size of an Airbus A320 is moved through the air curtain. The function of the air curtain is only slightly influenced. Below the wings some cold air can enter the hangar but this is negligible as compared to the energy balance over the whole calculation time.

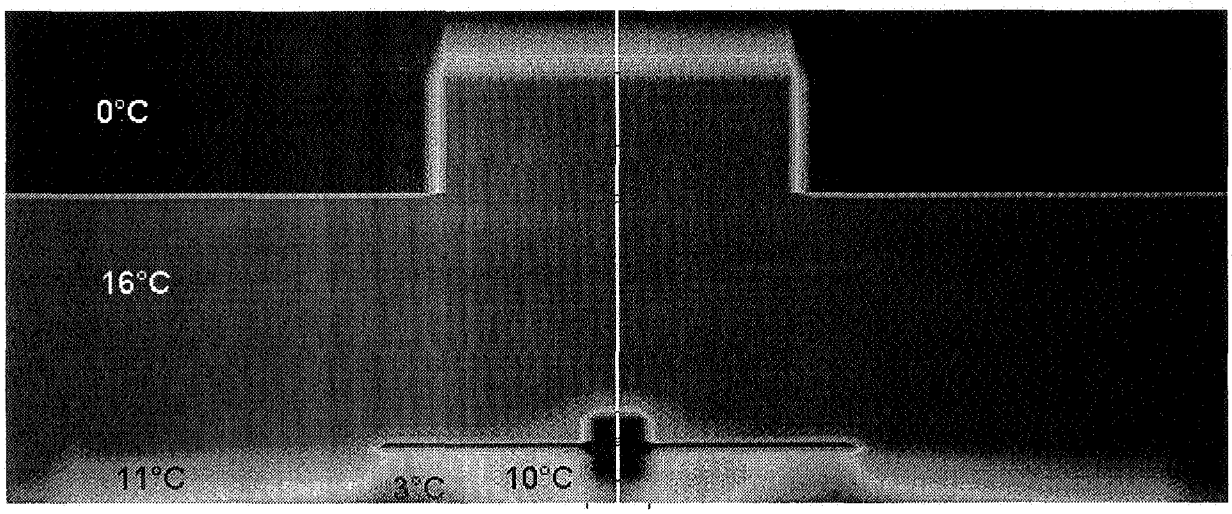


Figure 15: Air plane crossing air curtain in 3-dimensional case with air jet velocity of 18 m/s and external wind of 6 m/s. The calculation was done for only one half of the hangar. Some cold air can enter the hangar below the wings during the actual crossing, but the shielding effect over the whole calculation time is good.

The studies have shown the feasibility of air curtains and the potential for energy saving for such large doors. Whether the pay-back time is short enough to make the investment attractive from the purely economical point of view or not, depends very much on the the practical use of the fans (and on the energy cost). If the fans are used only for very short door openings as discussed here (in the order of 3 minutes), then they are not used a very long time (assuming 10 openings per night lasting 3 minutes each, during 120 nights, equals only 60 hours of use); if one door opening process lasts 15 minutes, the fans are used 300 hours, and the investment is more favourable. It is the practical experience of Swissair, that a door opening process is lasting 10-20 minutes. The actual energy saving for such a long door opening process must be investigated separately, because the energy saving, as compared to the case without air curtain, tends to decrease. The loss without air curtain decrease after some minutes when the hangar is filled with cold air, whereas the loss with air curtain remains constant.

5. Conclusions

Simple thermal zonal models and CFD models have been applied successfully to the prediction of air flow through very large openings in aircraft hangars.

- The thermal zonal model combined with the gravity wave concept allows the prediction of the inside air cooling after opening of a hangar door. The agreement with the experimental curves is very good in view of the simplicity of the model.
- The temperature recovery time after closing depends on the opening time, the time constant for heat transfer and the auxiliary air heating power.
- The recovery time can be shortened by using high power hot air blowers for a short period of time; the hot air stream should reach floor level. A floor heating system cannot deliver the required power and has a time constant which is too long.
- The CFD calculation yields velocities in the door planes which agree well with the the velocities obtained by the gravity wave concept.
- The CFD results using laminar flow (i.e. no turbulence model) agree well with the observation that the warm air in the volume above the door level is kept inside the hangar. This feature was not obtained using the wide-spread k-ε turbulence model.
- A parameter study was performed to obtain feasible design parameters for huge air curtains in the door plane to reduce heat losses when air planes are entering or leaving the hangar. The 3-dimensional study allows an estimation of the energy saving potential of such air curtains.

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