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A New Integrated Design Tool for Naturally Ventilated Buildings Part 2: Integration and Application

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A major problem in the design of naturally ventilated buildings is the complicated interaction between the flow rates and the indoor air temperatures. The natural ventilation flow rates are influenced by the indoor air temperatures while the indoor air temperatures are in turn influenced by the flow rates. A good design tool should therefore consist of a flow model to determine the flow rates and a thermal to determine the indoor air temperatures. These two should be solved simultaneously in an integrated manner. Existing design tools lack the ability to address this.

This paper describes the implementation and verification of the new flow model derived in Part 1 of this paper into such an integrated natural ventilation design tool. The thermal model is based on existing theory that has been verified extensively. An iterative solution algorithm is employed to ensure simultaneous solution of these two models.

Continuous tracer gas and temperature measurements show that the integrated tool can be used with confidence in the design of naturally ventilated buildings. A case study is also presented that illustrates how the new tool can be used successfully to optimize the design of a naturally ventilated factory building.

INTRODUCTION

IN Part 1 of this paper [6] a literature review was presented that showed that at present no integrated design tool exists for naturally ventilated buildings that properly accounts for both wind and thermal effects as well as the important interaction between these two.

Interaction between the thermal and flow models

Pressures on the building envelope that result in natural ventilation arise from both wind and thermal effects. The thermally induced pressures are caused by the difference in temperature between the indoor and outdoor air which results in a difference in density between the indoor and outdoor air. This difference in density induces flow through the building. Being able to predict the indoor air temperature is therefore an important characteristic of any good natural ventilation design tool.

The indoor air temperature is, among other things, dependent on the thermal characteristics of the building, the atmospheric conditions such as temperature, humidity and radiation, the interior loads in the zone and also the introduction of fresh air into the zone. The indoor air temperature is therefore dependent on the natural ventilation flow rate.

The interdependence of the indoor air temperature and the natural ventilation flow rate necessitates an integrated design tool. It should consist of a flow model as well as a thermal model and it should account properly for the important interaction between these two. In Part 1 of this paper [6] a new ventilation model was derived and verified for implementation in such an integrated design tool.

The ventilation model

The ventilation model derived earlier takes into account the effect of both wind and thermal forces on the natural ventilation flow rate. In calculating the flow rate a number of simplifying assumptions are made. The effects of the following parameters are considered: the layout of the building, the permeability and height above ground level of each opening, the wind speed and direction as well as the surrounding terrain and shading effect of other buildings.

The model requires no measured input data or detailed description of the outside geometry of the building which makes it extremely suitable as a design tool. From the verification study it was concluded that the effect of thermal forces is correctly taken into account but that the effect of the wind is slightly underestimated. It is important to note that ventilation due to thermal forces will only occur when two or more openings at different heights are provided in the building envelope.

This paper describes the implementation of the new flow model derived in Part 1 [6] into a new integrated natural ventilation design tool.

Summary

- The interaction between the thermal performance of a building and the natural ventilation flow rates must be accounted for.

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- At present no integrated design tool exists that takes into account this important interaction.
- The ventilation model derived earlier takes into account the effect of both wind and thermal forces on the natural ventilation flow rate.
- The verification study showed that the effect of thermal forces is correctly taken into account but that the effect of the wind is slightly underestimated.
- This paper describes the implementation of the new flow model derived in Part 1 [6] into a new integrated natural ventilation design tool.

IMPLEMENTATION

The proposed ventilation model was integrated with the EASY building thermal analysis program [1]. The model is similar to that used in the QUICK program [2–4] but has been revised to include the prediction of surface temperatures and certain multi-zone temperature effects. A description of the thermal model and the integration of the flow and thermal models is given below.

Thermal model

The thermal model is based on an electrical analogue design-day calculation procedure and has been implemented in a user-friendly design tool that allows the analysis of a single zone at a time. It includes *inter alia* the modelling of hourly varying interior convective, radiative and latent loads, direct solar gains taking into account external shading devices and building orientation, multi-layered walls, roofs and high-mass floors either suspended or in ground contact.

Given the building geometry and hourly values for climatic temperature, humidity and radiation as well as hourly values for internal loads, the model can be used to predict the resultant hourly indoor air temperatures or to calculate air-conditioning loads for a specified indoor air temperature. The thermal model has been verified successfully for a wide variety of buildings [1, 4].

The loads due to air introduced into the zone are also taken into account given the flow rates and the supply air temperatures for each hour. In the case of an air-conditioning system the temperatures and flow rates can be specified. In the case of natural ventilation or infiltration, the supply air temperature would be equal to the specified outdoor air temperatures. The flow rates must be calculated using the appropriate flow model.

Integration

The ventilation model has been derived for a multi-cellular structure. However, it was implemented in the design tool as a single-zone model to conform to the assumptions of the thermal model. This implies that there will be only one internal node. This greatly simplifies the specification of the network layout as well as the numerical solution. Although this places a restriction on its applicability, it favours simplicity which is a crucial criterion for any design tool. Furthermore, the typical building types in which natural ventilation is usually employed can in most cases be considered to approximate single-zone buildings.

To further simplify the data requirements, the input for the ventilation model is not required on an hourly basis. If it were, it would mean that the designer would have to specify the wind speed and direction for each hour during the day as well as the permeability of each opening on the envelope for each hour of the day. Instead, provision is made for three periods during the day for which the wind speed and direction is taken as constant and for which the permeability of each opening can be specified.

In the main ventilation input screen the type of flow into the zone may be specified as either 'ventilation' in which case the permeability data for openings are used, 'infiltration' in which case the wind speed data and building type description are used together with the empirical model for infiltration, or a user 'specified' flow rate and supply temperature. This specification of the flow type can be different for each hour of the day. Windows can therefore be open (ventilation) or closed (infiltration) during the day or at certain times an air-conditioning system (specified flow and temperature) can be switched on.

To provide for the interaction between the thermal and flow models an iterative solution algorithm is employed. The calculation is initiated by guessing values for the indoor air temperatures. These indoor temperatures together with the specified outdoor air temperatures are used as input to the flow model which is then solved for the flow rates. These flow rates are used as input to the thermal model which in turn predicts the indoor air temperatures. This process is repeated until convergence.

Summary

- The thermal model accounts for all the important thermal characteristics of any building and is able to predict hourly indoor air temperatures.
- The model has been verified successfully for a wide variety of buildings.
- To conform to the thermal model the ventilation model was further simplified to a single-zone analysis.
- To provide for the interaction between the thermal and flow model an iterative solution algorithm is employed in which the thermal and flow models are solved in turn until convergence is obtained.

VERIFICATION

Although the verification of both the ventilation and infiltration models has been discussed earlier, it is also essential to form an idea of the accuracy of the complete integrated design tool. For this reason further measurements of both air flow rate and temperature were conducted in a building on a continuous basis for a number of days.

The ideal situation in which to conduct these measurements would probably be a large factory building with roof ventilators and rather high interior loads. Natural ventilation is usually employed in such a case where high interior loads cause the indoor temperatures to rise above the outdoor air temperature. The outdoor air flow through the building is then used to cool the building. However, several practical problems are encountered in determining the flow rates through such a large building.

The decay rate tracer gas technique requires that the tracer gas injected into the zone should be thoroughly mixed with the indoor air. Furthermore, a representative indoor air temperature must be measured. For this reason a much smaller zone was selected, namely a room in a house which unfortunately had small interior loads. Despite the fact that this is not a typical case, a good idea can still be formed of the accuracy of the simulations.

Measurements

The measurements included the following: outdoor air temperature and relative humidity, global and diffuse radiation outside the building, wind speed and direction, indoor air temperature and also ventilation flow rates through the zone by making use of the decay rate tracer gas technique.

Measurements were taken continuously for a number of days. After inspection of the data two consecutive days were chosen for which the results were very similar. The measured values for these two days were then averaged for each hour of the day to derive measured data for a single steady state day which could be compared to the design-day simulation.

The room has an internal volume of 44 m^3 and its outer walls are constructed of double layer dark brown face brick with an air space in between. It has a clear glass sliding window of 1.92 m^2 facing north at 3.7 m above ground level and one of 3.55 m^2 facing south at 1 m above ground level.

For the experiment both these windows were opened partially between 06:00 and 18:00 with a discharge area of 0.2 m^2, and closed during the night. The discharge coefficients for both windows were taken as 0.65 which represents an unobstructed opening with a simple geometry as is the case here. The single internal door between the room and other zones was closed throughout. The room contained only a very small internal load of approximately 150 W during the day when the computer controlling the tracer gas measurements was running.

The tracer gas was injected into the room at intervals of fifteen minutes by opening an automatically controlled solenoid valve for fifteen seconds. A single fan was used at very low rotational speed to aid in mixing the tracer gas with the indoor air. The tracer gas concentration was sampled every thirty seconds and stored on computer disk together with the time of the sample. Figure 1 presents a typical result of the measured tracer gas concentration. These data were obtained between 11:00 and 12:00 on the second of the two days selected. The processing of these data warrants some attention and will be discussed briefly.

If sufficient mixing is achieved the tracer gas concentration in the room can be assumed to be given by

$$C = C_o e^{-rt} \tag{1}$$

with C the gas concentration at time t and C_o the original concentration. r will be the ventilation rate in air changes per hour provided that t is measured in hours. To determine the ventilation rate one may now choose a certain point on the measured concentration curve (Fig. 1) and determine how long it will take for one air change to take place by setting rt equal to one. One air change would therefore have taken place when $C = (1/e)C_o$ or $C = 0.368C_o$. The time can then be inverted to obtain the flow rate in air changes per hour.

This method of data processing can however result in problems. It means that one has to have an idea beforehand of how long one air change will last so as not to start a new cycle prematurely by injecting gas again before one air change has taken place. If the flow rate through the room is very low, it may for instance take more than fifteen minutes for the concentration to decrease to the required value.

A more robust way of looking at the data is by writing equation (1) as follows [5]:

$$\ln C = -rt + \ln C_o. \tag{2}$$

This shows that if the concentration is plotted on a logarithmic scale against time, the ventilation rate is equal to the slope of a straight line curve fitted through the data points. This method was used here. Figure 2 shows the data of the previous figure with the concentration plotted on a log scale.

The figure shows that the data approximate straight line curves except in the second set of data which implies that the ventilation rate changed slightly during the cycle. However, by fitting straight lines through each of the data sets, an average ventilation rate can be determined for each hour. Figure 3 shows the hourly average measured air changes per hour for those hours when the windows were open.

Figure 4 shows these air change rates versus the measured wind speed at roof height and the measured indoor/outdoor temperature difference. The dependence of the flow rate on both the wind speed and temperature difference can be seen from the figure.

Simulated results

The first simulation was conducted by specifying the measured values of the air change rates into the room. This was done to investigate the accuracy of the thermal model for given flow rates. Figure 5 shows the resultant predicted indoor air temperatures together with the measured indoor and outdoor air temperatures. From the figure it seems that the effect of the flow is slightly exaggerated since the predicted indoor air temperature is in some cases closer to the outdoor air temperature than it should be.

Figure 6 shows the predicted indoor air temperatures together with the measured indoor and outdoor air temperatures obtained with the complete integrated design tool. The natural ventilation flow rates were therefore calculated using the flow model described earlier. The figure shows very good agreement between the measured and predicted values with a maximum error of 1.1°C and an average of 0.3°C.

Figure 7 shows the hourly averaged measured air changes per hour together with the predicted flow rates. From the figure it is clear that the flow rates are in general underestimated. This result is consistent with the earlier conclusion that the effect of the wind on the ventilation rate is underestimated since the wind played a crucial role in this case.

From the figure one can also clearly see the effect of the three distinct periods for which the wind speed and

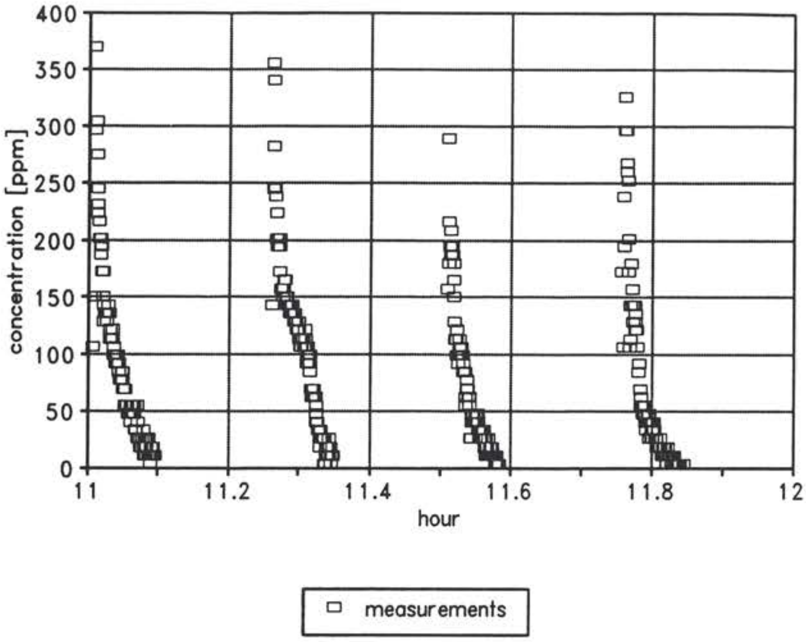

Fig. 1. Measured tracer gas concentration in the room between 11 : 00 and 12 : 00.

direction is averaged and taken as constant. The first period stretches from 07 : 00 to 10 : 00, the second from 11 : 00 to 15 : 00 and the third from 16 : 00 to 18 : 00.

The difference in predicted flow rate between 09 : 00 and 10:00 is interesting. One would have thought that since the same wind speed and direction is specified, and because the predicted temperature differences between the indoor and outdoor air are approximately the same at 1.1°C and 1.0°C, the predicted flow rates would be approximately equal. However, Fig. 6 shows that the sign of the temperature difference changes between 09 : 00 and 10 : 00. This clearly shows that flow rates due to wind and those due to thermal forces are not simply additive.

In summary it seems that in the ventilation model the effect of thermal forces on the flow rate is correctly taken into account while the effect of wind is underestimated. In the thermal model the effect of the flow on the indoor air temperature is slightly exaggerated.

The implications of these conclusions are important. The fact that the wind effect is underestimated is probably not a bad characteristic since it will tend to make design calculations slightly conservative. Since ventilation is usually required to remove heat generated by high internal loads, actual flow rates higher than those predicted by the design tool will be welcomed.

However, the worst case design scenario for natural ventilation is typically when there is no wind and only flow due to thermal forces prevails. In this case the ven-

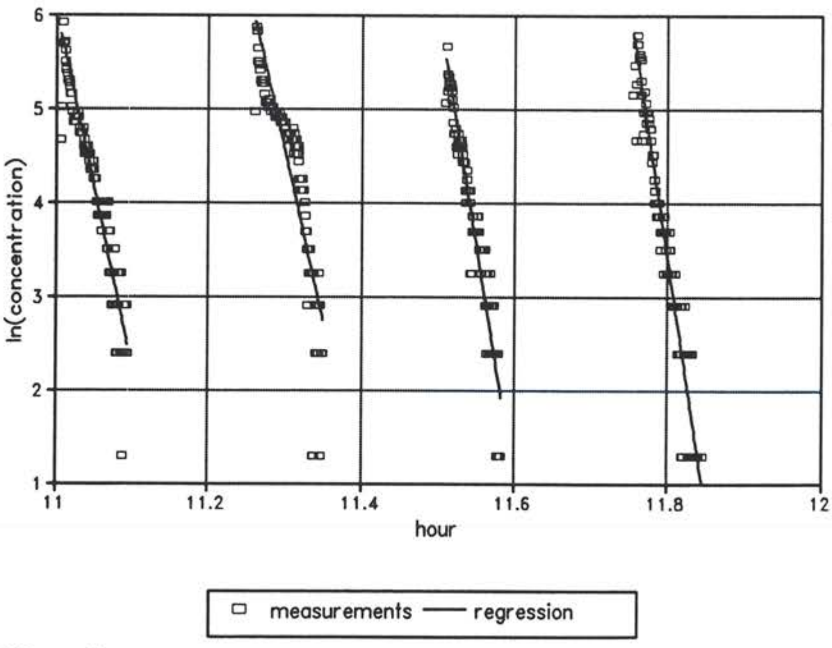

Fig. 2. Measured tracer gas concentration in the room between 11 : 00 and 12 : 00 plotted on a log scale.

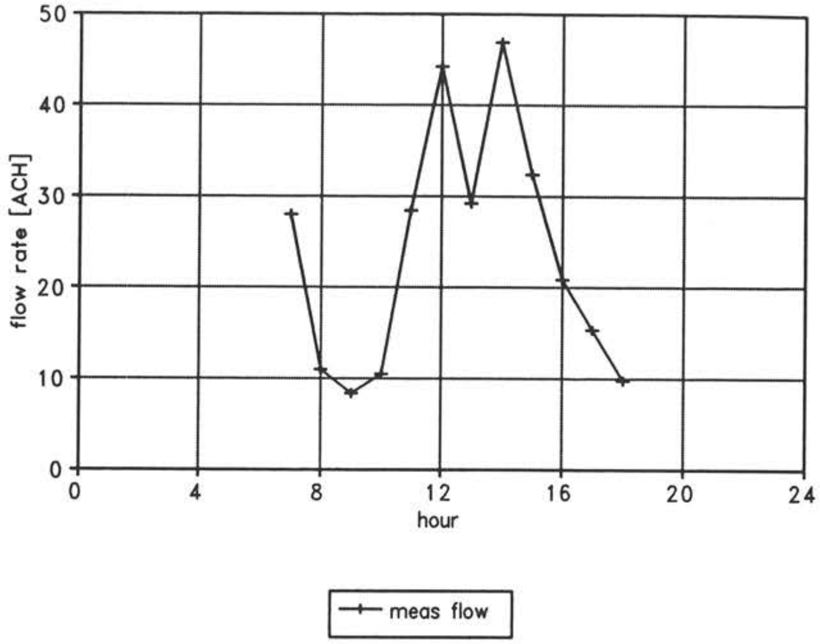

Fig. 3. Measured air changes per hour averaged for each hour while windows were open.

tilation model should provide acceptably accurate results. The fact that the effect of the flow on the indoor air temperatures is slightly exaggerated is undesirable. If the designer investigates the case with no wind, the design tool might predict slightly lower temperatures than will actually prevail and the resultant ventilation devices may be underdesigned.

It is also important to note that these conclusions are drawn on the assumption that the measured flow rates are absolutely accurate. Although care was taken during the measurements, a simple constant error factor in the concentration measurements will tend to change the gradient of the straight lines in Fig. 2 and therefore also the measured air change rates. It is however important that the effect of the flow rates on the thermal model be investigated further. Future work will therefore include an experiment similar to the one carried out here, but with the air flow supplied mechanically and measured in a more fundamental manner.

Another question that arises from the results presented above is whether the flow rate has much effect at all. The rather large difference between the measured and predicted flow rates resulted in a small deviation in predicted indoor air temperatures between Figs 5 and 6. To clarify this Fig. 8 shows the predicted indoor air temperatures with and without ventilation.

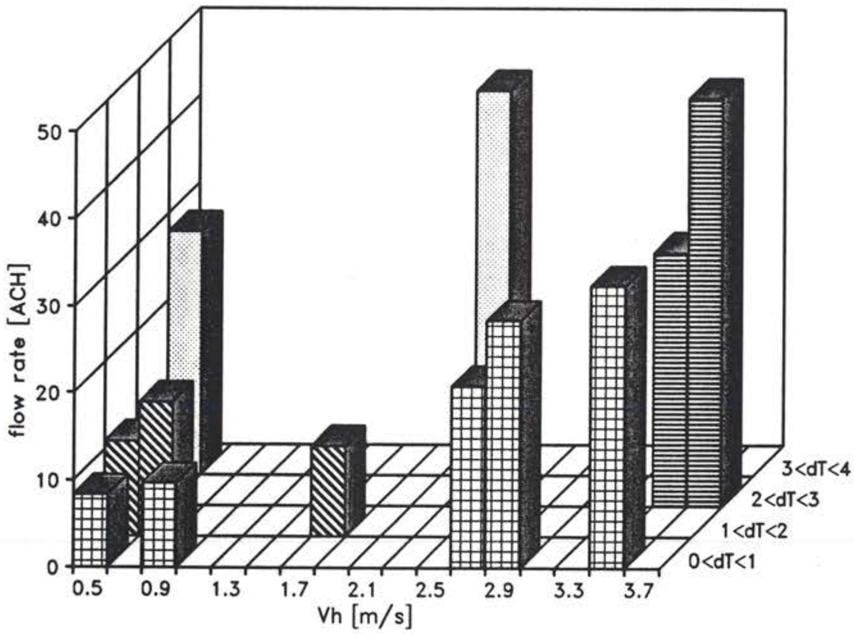

Fig. 4. Hourly averaged measured air changes per hour versus wind speed and temperature difference between the indoor and outdoor air.

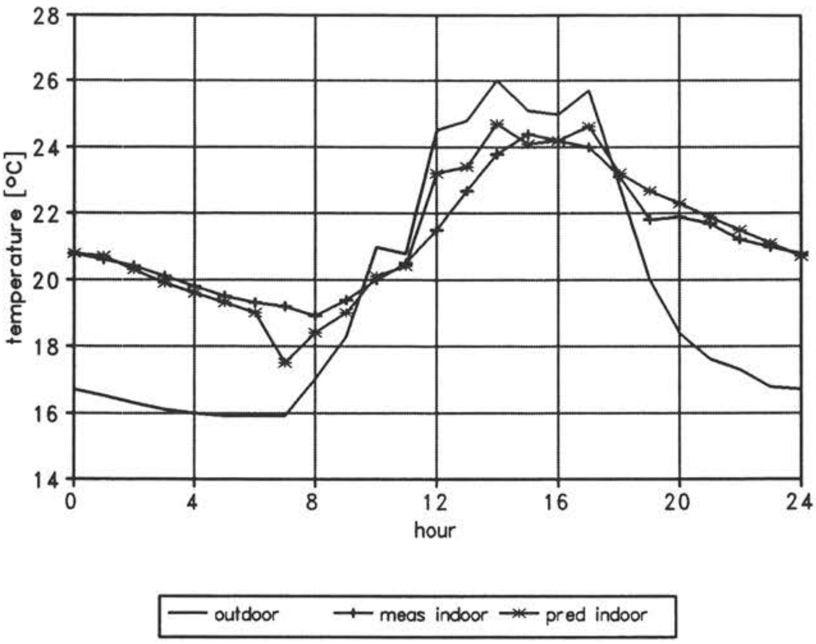

Fig. 5. Measured outdoor air temperatures together with measured and predicted indoor air temperatures obtained with the measured values of air changes per hour specified into the room.

From the figure it is clear that a notable difference is obtained especially between 12:00 and 18:00 which illustrates the importance of accounting for the flow rates. These temperatures also show that this is not a typical natural ventilation design case since the outdoor air flow actually heats up the building instead of cooling it down.

Summary

- Continuous temperature and flow measurements were conducted to verify the integrated design tool.
- Comparison between measured and predicted flow rates confirmed that the effect of wind on the ventilation rate is underestimated.
- The effect of the flow is slightly exaggerated by the thermal model.
- Acceptable indoor air temperature predictions were obtained with the integrated design tool which showed that the tool can be used with confidence in the design of naturally ventilated buildings.
- The simulated results also illustrated the fact that the flow rates due to wind and thermal forces are not simply additive.

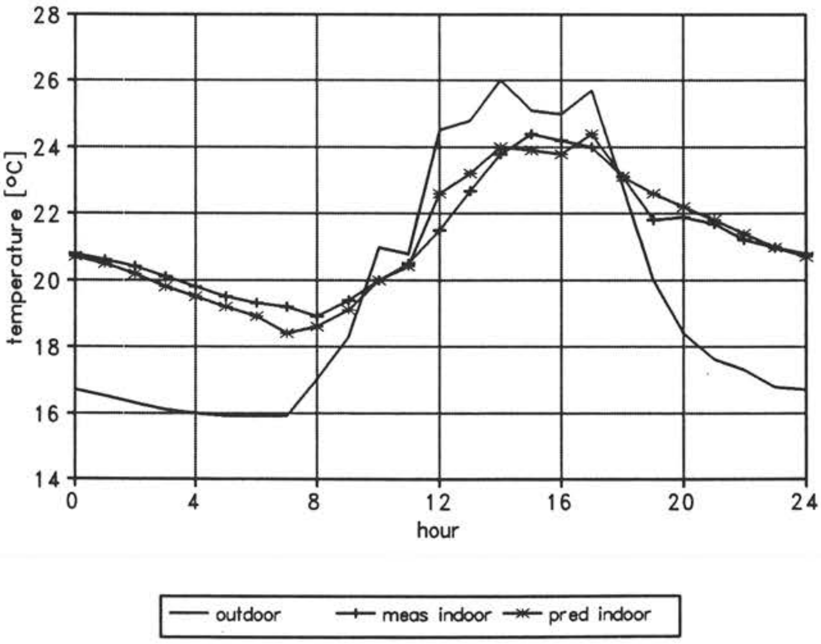

Fig. 6. Measured outdoor air temperatures together with measured and predicted indoor air temperatures obtained with the complete integrated design tool.

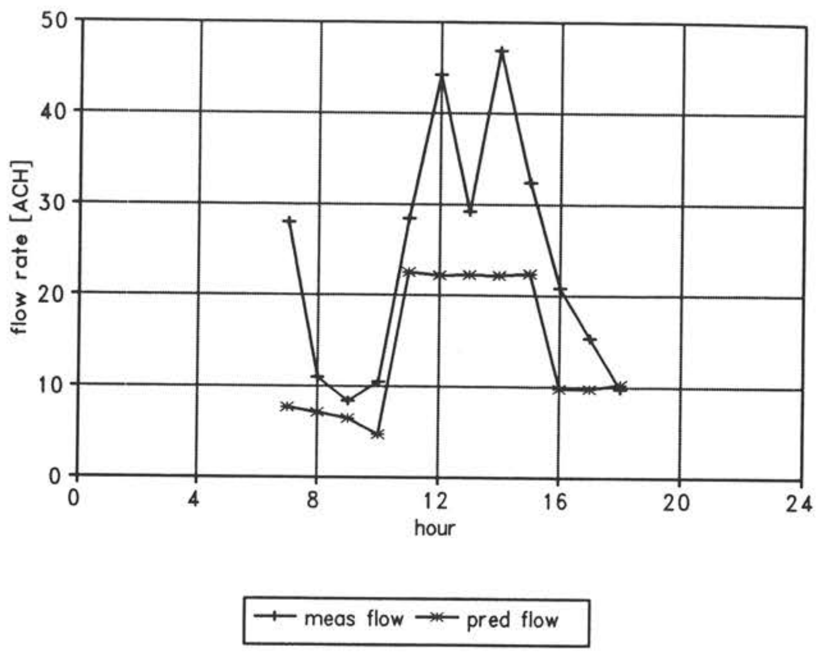

Fig. 7. Measured and predicted air changes per hour obtained with the complete integrated design tool.

CASE STUDY

This section presents a case study to illustrate how the new integrated design tool may be used to optimize the passive design of a factory representing a typical natural ventilation design case.

Building geometry and loads

The building studied here is a factory constructed of sheet metal. The building is shown schematically in Fig. 9.

The factory has a floor area of 1250 m^2 and an internal volume of 18 750 m^3. It contains high interior mass and a total interior load of 100 kW due to machines. The building is occupied by 20 people between 07:00 and 18:00. It has windows along the side of the north and south walls with a total openable area of 150 m^2. The roof may be fitted with ventilators but at this stage the exact geometry is not known. The factory is situated in the East London area in the Cape Province of South Africa. In South Africa the main thermal problem in such a factory is encountered in summertime when outdoor air temperatures are high. For the purpose of the demonstration a windless summer design day will be used.

Passive design

Two of the most important measures for thermal comfort used in a factory like this are insulation and natural ventilation. Since the addition of insulation on for instance the roof has an important effect on the thermal performance of the building, it will greatly influence the results produced by the thermal model. Since there is such a complex interaction between the thermal model and the flow model, the optimization of the building design with regard to insulation and natural ventilation is also complex.

In order to optimize the design the aim will be to minimize the initial cost of the building for the best possible degree of thermal comfort inside. It is important to note that the capital cost of both insulation and roof ventilators are directly proportional to the area covered. A number of questions should therefore be addressed during the design stage, namely the following.

- Is it necessary to spend any money to provide measures aimed at improving thermal comfort?
- Will it be worthwhile to spend money on roof insulation?
- Will it be worthwhile to spend money on roof ventilators?
- Which one of these two measures will ensure the most cost-effective solution?
- If roof ventilators are fitted, how much money should be spent to provide the optimum amount of ventilation?
- Could a combination of insulation and roof ventilators not be used to provide the best solution?

Each of these questions can be investigated with the new tool.

Indoor air temperatures with no insulation or ventilation provided. The first aspect that must be investigated is whether it will be necessary to provide any insulation or ventilation at all. The first simulation carried out with the new tool is therefore the case where no insulation is provided and only unintentional infiltration is allowed. The building is specified as a 'very leaky' building. Figure 10 shows the results. As expected the indoor air temperature will rise very high during the day with a maximum of almost 42°C. This is clearly unacceptable and probably a good recipe for labour problems.

The effect of insulation. To investigate the effect of insu-

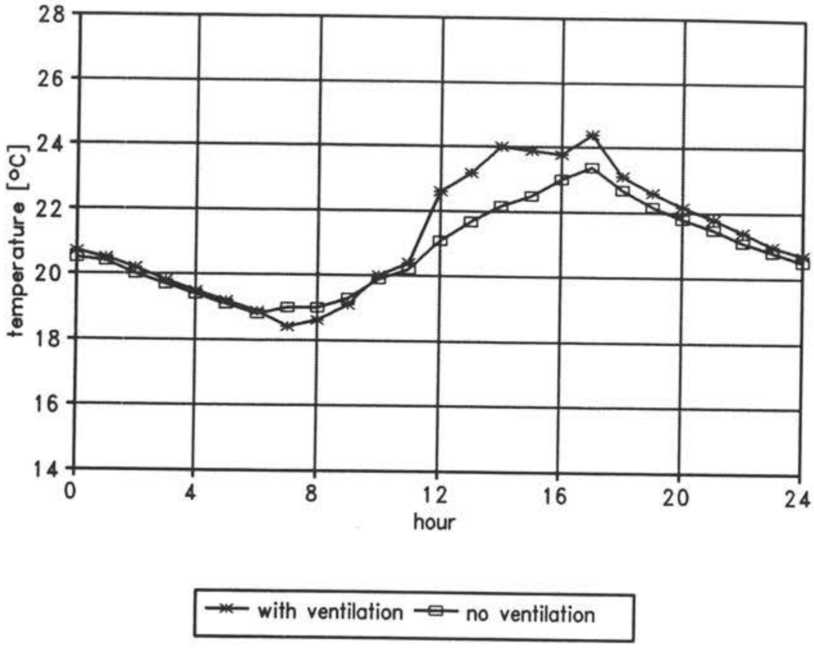

Fig. 8. Predicted air changes per hour obtained with the complete integrated design tool with ventilation and without ventilation.

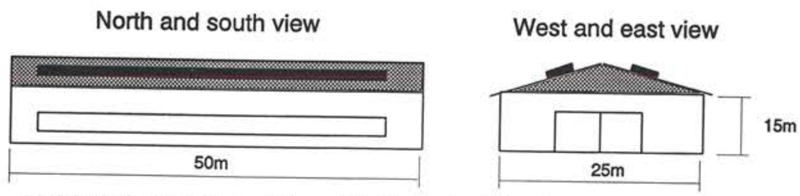

Fig. 9. Schematic representation of the factory building designed in the case study.

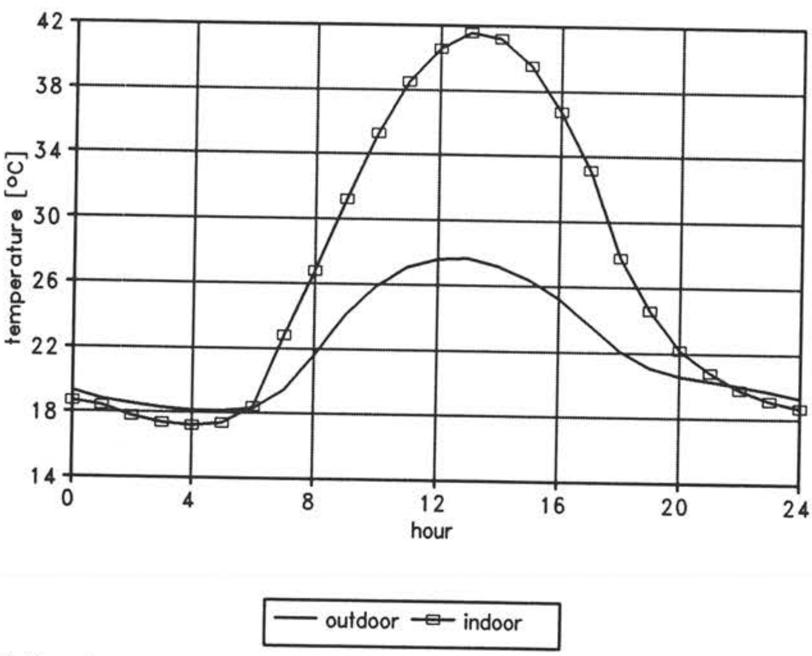

Fig. 10. Outdoor air temperatures and predicted indoor air temperatures with no ventilation or insulation provided.

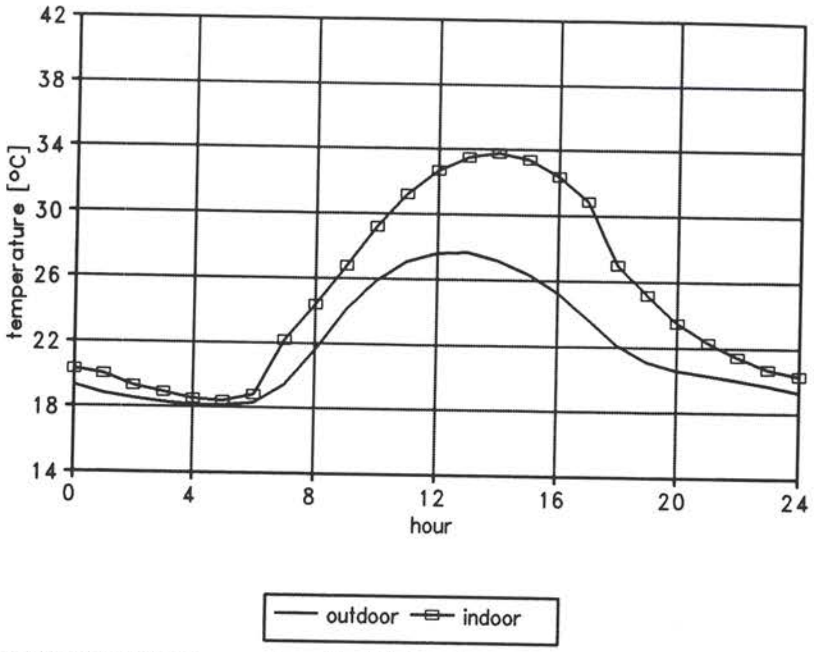

Fig. 11. Outdoor air temperatures and predicted indoor air temperatures with 50 mm thick insulation provided underneath the roof.

lation the next figure shows the resulting temperatures for the case where a mineral wool blanket of 50 mm thickness is attached to the bottom of the corrugated iron roof. From Fig. 11 it is clear that the maximum indoor air temperature is drastically reduced to around 34°C. It is important to realize that the effect of the roof insulation is mainly to reduce the load induced by radiation of the outside of the roof. The effect of internal loads is however not addressed.

The effect of ventilation. As opposed to insulation, ventilation aids in removing internal loads caused by heat generation from the zone. As shown earlier the effectiveness of the ventilation is influenced by the total permeability of the building which is in turn determined by the total discharge area of the ventilation openings. The area of roof ventilators used in a factory such as this is usually expressed as a percentage of the floor area and ten per cent is usually regarded as an upper limit. To illustrate the effect of ventilation, Fig. 12 shows the predicted indoor air temperatures for the factory with no insulation but with roof ventilators with a discharge area equal to 10% of the floor area.

The windows are only open during the daytime. Since

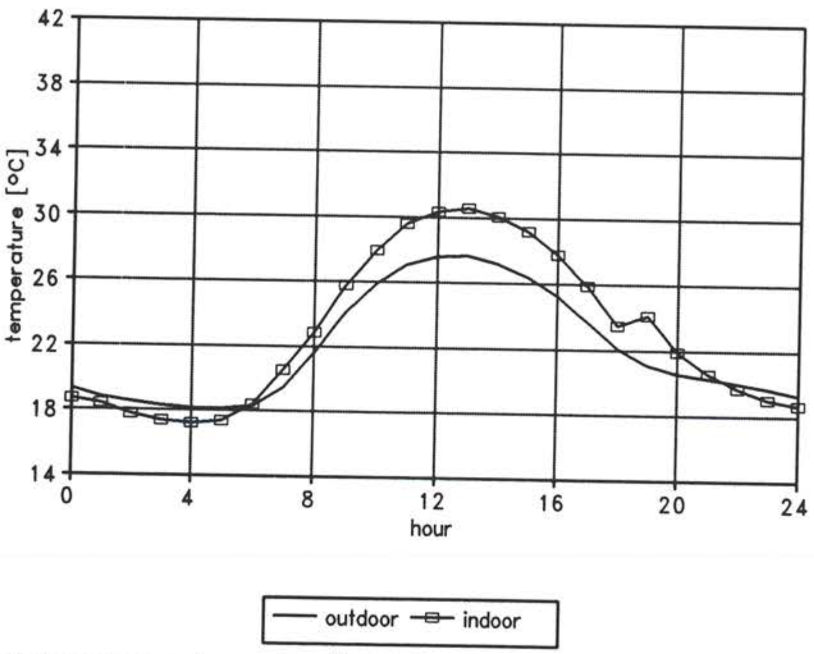

Fig. 12. Outdoor air temperatures and predicted indoor air temperatures with no insulation and roof ventilators equal to 10% of the floor area provided.

two or more openings are required at different heights above ground level and all the roof ventilators are situated at the same height, no large-scale ventilation will occur during the night. During the night only unintentional infiltration occurs.

The effect of ventilation on the indoor air temperature is even more drastic than that caused by the addition of insulation. The indoor air temperature is reduced from 42°C to just below 31°C. The slight increase in temperature at 19:00 is interesting. It is caused by the stored energy in the building structure and high internal mass and floors which is radiated into the zone even after the occupants have left the building. Remember that the windows are closed after 18:00 and the loads due to the stored energy are not removed instantly.

A question that must now be asked is whether it is really necessary to provide ventilators with an area equal to 10% of the floor area. In other words could a maximum temperature of less than 31°C not be achieved by spending less money. Figure 13 shows the results of an investigation aimed at determining the optimum amount of roof ventilator area.

From the figure one can see that the effectiveness of ventilation diminishes gradually as the ventilator area is increased. In this case roof ventilators with a discharge area equal to 7% of the floor area will be sufficient. Beyond this point the addition of 1% more ventilator area results in an improvement of less than 1% on the indoor air temperature.

Combined insulation and ventilation. The effects of insulation and ventilation have up to now been investigated separately. However, the most cost-effective solution could perhaps be obtained by combining these two. By using a combination the effect of both the external radiation of the roof and the removal of internal loads could be addressed simultaneously. The implication of such a strategy on the initial cost of the building must however be considered. To investigate this simulations were conducted with 50 mm of roof insulation installed together with different sizes of roof ventilator. Figure 14 represents the results of this investigation and shows the predicted maximum indoor air temperature versus the roof ventilator area expressed as a percentage of the floor area.

As shown in the figure the combination of insulation and ventilation results in much lower temperatures. Maximum temperatures of below 30°C can be achieved. It is also important to note that the reduction in the relative effectiveness of the ventilators with increased area is much more pronounced. Further addition of ventilator areas beyond 4% of the floor area represents improvements of less than 1% on the maximum indoor air temperature. It is therefore possible to fund all or part of the cost of the insulation from money saved by installing less roof ventilators. Figures 15 and 16 show the predicted indoor air temperatures and flow rates respectively for this case.

The fact that less roof ventilators are installed together with insulation will of course also have a beneficial effect in the winter. In wintertime internal loads aid in heating the building. Insulation will diminish the heat loss. In the case where ventilators cannot be closed in winter less ventilation area will also aid heat retention.

Summary

- In the factory investigated here natural ventilation alone provides better thermal comfort than roof insulation alone.
- The effectiveness of roof ventilator area is reduced gradually with the addition of more area. This means that the optimum amount of ventilator area for each specific design should always be investigated.
- The highest degree of thermal comfort is obtained with a combination of roof insulation and ventilation. By

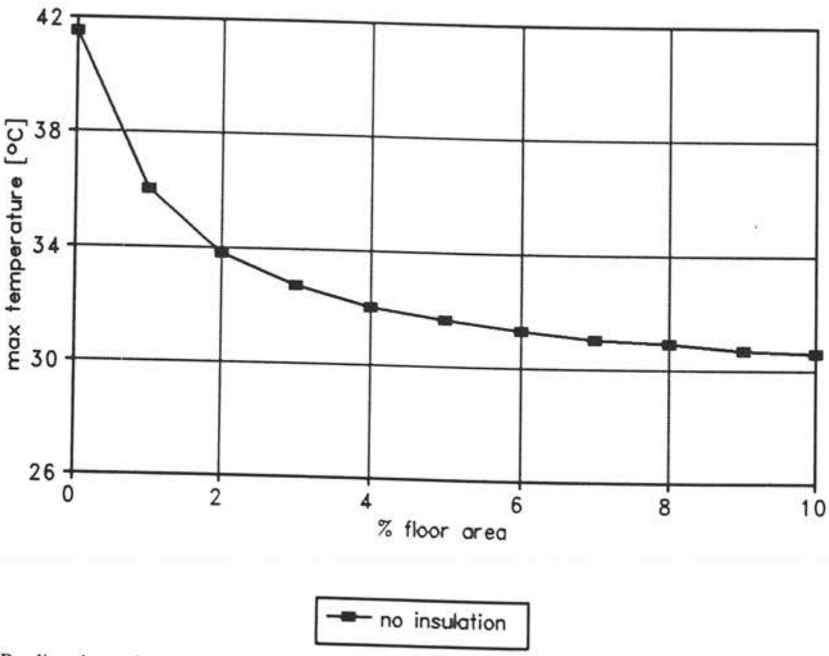

Fig. 13. Predicted maximum indoor air temperatures with no insulation and different numbers of roof ventilators expressed as a percentage of the floor area.

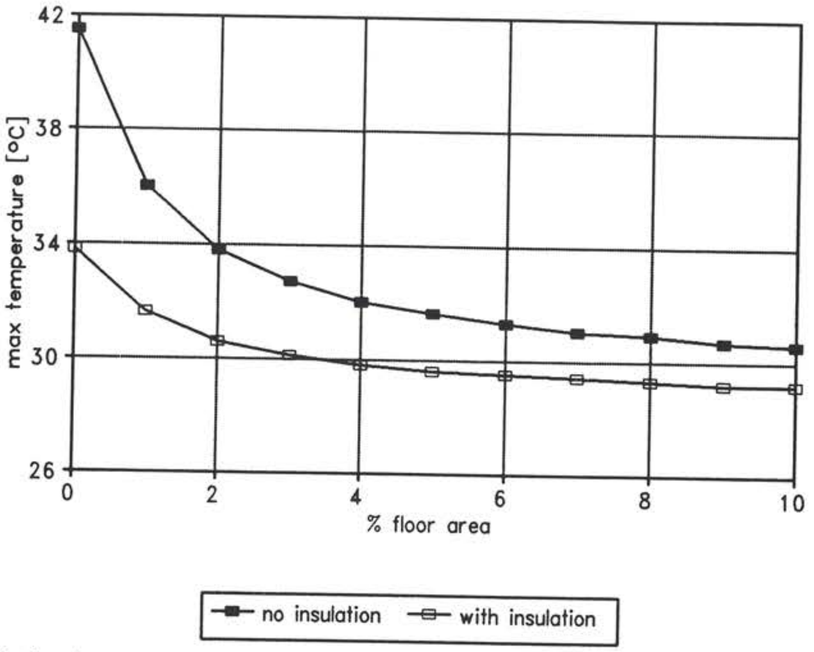

Fig. 14. Predicted maximum indoor air temperatures with 50 mm roof insulation and different numbers of roof ventilators expressed as a percentage of the floor area.

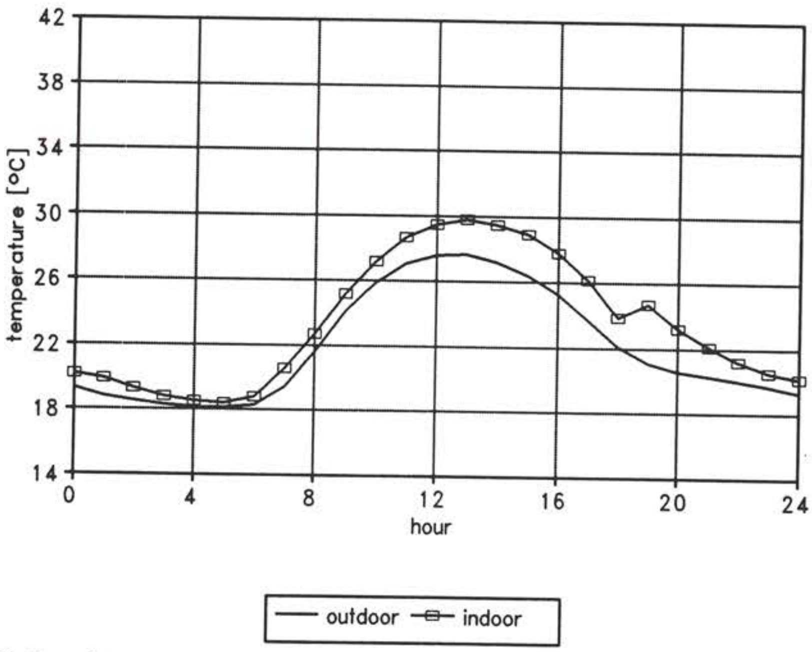

Fig. 15. Outdoor air temperatures and predicted indoor air temperatures with 50 mm roof insulation and roof ventilators with an area equal to 4% of the floor area.

optimizing the ventilation design the cost of the insulation can be partially or totally funded from the savings in the cost of ventilation devices.

- These investigations could not be carried out without the new tool which accounts for both the thermal performance and the natural ventilation flow rates in an integrated manner.

CONCLUSION

The literature review presented in Part 1 of this paper [6] showed that at present no integrated design tool exists that takes into account the important interaction between the thermal performance of a building and the natural ventilation flow rates. This paper discussed the integration of the new ventilation model derived in Part 1 [6] into such an integrated design tool. The design tool provides for the analysis of typical single-zone buildings and uses an iterative solution algorithm in which the thermal and flow models are solved in turn until convergence is obtained.

Continuous temperature and tracer gas flow measurements were conducted to verify the integrated design tool. Comparison between measured and predicted flow rates

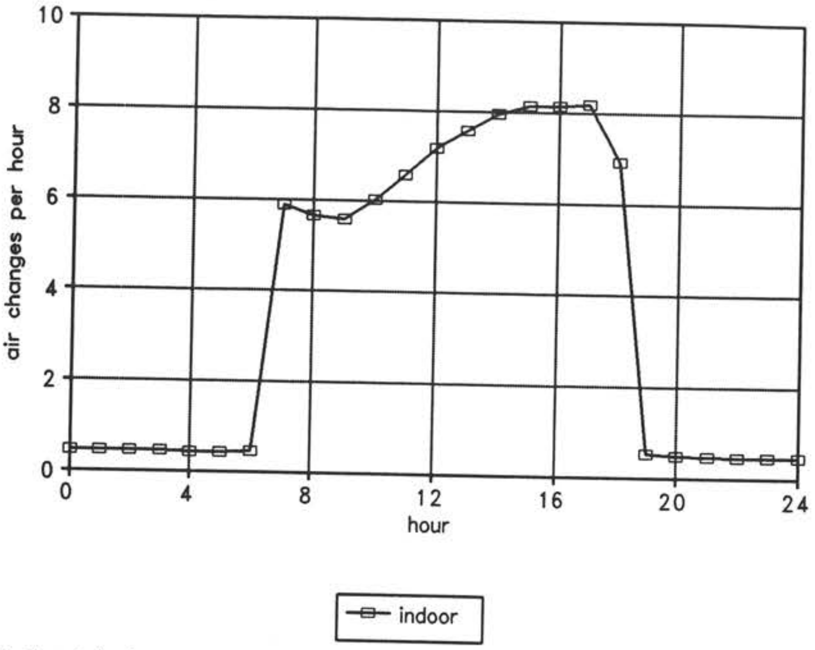

Fig. 16. Predicted air changes per hour with 50 mm roof insulation and roof ventilators with an area equal to 4% of the floor area.

showed that the effect of wind on the ventilation rate is underestimated as was concluded in Part 1 [6]. The measurements also showed that the effect of the flow is slightly exaggerated by the thermal model. Despite this accurate indoor air temperature predictions were obtained with the integrated design tool which showed that the tool can be used with confidence in the design of naturally ventilated buildings.

Further investigations should be conducted to study the effect of the flow on the thermal model. Such investigations should include experiments where a known amount of outdoor air is provided mechanically and the flow rate measured accurately. The correct flow rates can then be specified in the design tool and the measured and predicted indoor air temperatures can be compared. It is important however that measured and predicted flow rates for the test building should first be compared for the case where no ventilation is provided to establish a base case which will ensure that only the effect of the flow is investigated in the final measurements. Furthermore, high internal loads should preferably be present to ensure a pronounced effect of the ventilation on the indoor air temperatures.

In the case study the complex interactions between the thermal and flow models were illustrated by investigating the combined effect of natural ventilation and roof insulation. The effectiveness of roof ventilator area is reduced gradually with the addition of more area. This means that the optimum amount of ventilator area for each specific design should always be investigated. The highest degree of thermal comfort was obtained with a combination of roof insulation and ventilation. By optimizing the ventilation design the cost of the insulation can be partially or totally funded from the savings in the cost of ventilation devices.

The case study illustrated that investigations such as these cannot be carried out without the new tool which accounts for both the thermal performance and the natural ventilation flow rates in an integrated manner.

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