Experimental and Theoretical Modelling of Natural Ventilation in
Judson College, Elgin, Illinois

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Executive Summary

In this report we describe a series of laboratory experiments and supporting theoretical models in which we have explored the potential for natural ventilation in the new Library Building at Judson College. In particular, we have focused on the potential for natural ventilation driven through the double façade system and on the potential for solar heating in the façade to assist the ventilation. The experiments and modelling indicate the potential for this design to work effectively, and has been used in the design and development of the façade system for the actual building. We also report on some experiments in which we have explored different designs for the termination for the stacks, so as to optimise the benefits of both wind-driven ventilation and buoyancy driven flow. Our work has been implemented in the design of the building through a series of meetings with Alan Short, Adam Whitely and Lauren Scully of Short and Associates.
1 Introduction

The new library project at Judson College has been designed as a low energy building. Natural ventilation coupled with thermal mass plays a central role in the strategy for regulating the thermal comfort within the building, especially in the spring/autumn seasons and potentially winter, when conditions are compatible with the use of natural ventilation.

We were commissioned to explore the possible designs for the natural ventilation in conjunction with Short and Associates. After some initial discussion of different designs, we converged on a solution for a double-façade for the office part of the building, to optimise the role of solar gains in spring and autumn in driving the ventilation flow, and on a new stack termination system to optimise wind assistance for the ventilation at the stack terminations.

We then carried out a detailed study of the natural ventilation flows in the office part of the building using an analogue experimental model. In particular, with this model, we explored the ventilation flow (i) in the double façade system, including the effects of solar heating within the façade, and (ii) using the new design for the stack terminations. Much of our study was applied to the upward displacement ventilation regime, in which air enters at the base of the building, is heated on different floors and then rises through the stacks to vents at high level in the building. The office part of the building formed the focus of our experimental study since it is this area in which our new design could have a substantial impact (Figure 1.1).

![Figure 1.1 Early version of office elevation](image)

We have also worked in a general consultancy mode with the design team in discussing other aspects of the overall strategy for natural ventilation and its detailed implementation in the building.

We report here on the study of the double façade system, with some recommendations for the design. Many of these recommendations have in fact been taken on board in the design of the building, including implementation of both the façade and stack termination concepts.
2 Experimental Model

We built a small-scale Perspex model of the building, as shown in figure 2. The model is placed in a water bath, to provide a dynamically similar, but small-scale analogue of the natural ventilation flows in the real building. In order to explore the effect of multiple storeys but keep the size of the experiment manageable, we included two floors in the experimental model.

![Perspex model of two floors of offices in DADA wing. Offices in foreground (left) and double façade in foreground (right).](image)

The façade of the building includes a gap between the interior and exterior glazing. This gap is divided into two vertical chambers: an inflow stack, which supplies air from below the ground floor upwards into the rooms on each floor; and an outflow stack, which draws air from each floor and allows it to rise to the top of the model building and vent to the exterior.

In the model, there is a high resistance wire coiled onto a plate placed on each of the two floors of the building to simulate the heat loads within the offices, as well as a third high resistance wire coiled onto a plate placed in the outflow stack as an analogue of solar heating within the façade. To generate a heat load, a current is passed through the high resistance wire, which then heats up. Since the wire is arranged in a coil, the heat load is uniformly distributed across the floor plate, as a model of a distributed heat load comprised of people and equipment within the space.

The design of the façade into two main stack systems, one to supply air to the offices and one to draw air from the offices, effectively isolates the flow through each floor, and we do not expect any reverse flows on either floor.

The experiments are designed to explore the ventilation flows under a range of conditions, and to measure temperatures throughout the building using an array of thermocouples connected to a digital recording system. Flow patterns and rates are visualised using dye studies, as illustrated in the experimental photographs shown in the following sections.
2.1 Experimental Investigation of the Façade System

We conducted a series of experiments, in which a heat load was applied to each of the floors in turn, and then to both of the floors together. The temperature in each floor and in the stack was measured, and compared, in order to assess the effectiveness of the natural ventilation. In particular, we examined the ventilation which may be driven through one floor with relatively little heat load, as a result of a heat load on the other floor.

In these experiments, we found that the floor with the heat load developed a substantial ventilation flow, while the other floor experienced much weaker secondary ventilation. With the heat load on the lower floor, the stack effect was greater, and so the ventilation flow larger, although the double façade system drove very effective ventilation through the heated floor in both cases. With a heat load on each floor (leading to twice the total heat load), the ventilation was more vigorous, but the temperature in each floor did not decrease dramatically as the overall heat load in the space was greater.

2.2 Heating on Lower Floor

![Figure 2.2 Experimental recording of temperature as a function of time in which the heat load on ground floor is 245W.](image)

It can be seen from Figure 2.2 that in the case of heating on the ground floor at 245W, the temperature of the ground floor is 12.2°C in excess of the exterior fluid. The top line in this figure is the temperature on the ground floor; the two fluctuating temperature profiles show the temperature in the stack. It can be seen that the upper floor has a similar temperature to the exterior. Note that these temperatures do not correspond numerically to the temperatures expected within the actual building – calculations later in the report estimate the temperatures expected in the actual building using models derived from the experimental data.
Figure 2.3 Photograph of the experiment with heating on the ground floor. The blue dye illustrates the mixing of air from the inlet stack, through the ground floor and up and out the stack. It may be seen that a small amount of the dye also passes through the upper floor, from the supply stack.

2.3 Heating on Upper Floor

In the following data, the heat load was placed on the upper floor of the model. Similar results as for the case of heating the ground floor are obtained, although the temperatures are higher for the same heat load since the distance from the upper floor to the top of the stack is smaller.

Figure 2.4 Temperature variations with a heat load of 245W on the upper floor.
It can be seen from Figure 2.4 that the temperature excess is now about 13.9 °C above the ambient, while with a heat load on the lower floor, the temperature excess was only about 12.2 °C.

![Figure 2.4](image)

**Figure 2.4** Photograph illustrating the flow pattern with a heat load on the upper floor and no heating on the ground floor.

From Figure 2.5 it can be seen that the dye illustrates a weak secondary ventilation flow on the ground floor with the main flow through the upper heated floor. The temperature within the stack fluctuates about a mean value which is smaller than the upper floor temperature owing to the slow flow of unheated air passing through the lower floor.

### 2.4 Heat Load on Both Floors

Experimental results from the case in which there is a heat load on both floors show a lower temperature of 11.1 °C on the lower floor (compared to 12.2 °C above) but a temperature of 13.8 °C on the upper floor, which is very similar to the temperature in the case in which the lower floor has no heat load.

![Figure 2.6](image)

**Figure 2.6** Temperature as a function of time in the case of heating on both floors.
It is interesting to note that even though the heat load is doubled, the temperatures are in fact a little smaller than in the case of heating only on one floor, owing to the greater ventilation flow through each floor. This is especially the case for the ground floor since the stack is now at a higher temperature than heating only from the ground floor owing to the inflow of warmer air from the first floor. As a result, there is a great flow through the ground floor, and hence a lower temperature.

*Figure 2.7 Photograph of the flow in the case in which there is a heat load on both floors. Both the lower floor (red) and upper floor (blue) are well mixed and vent into the common outflow stack. Note the photograph also emphasizes that there is no recirculation of air from the ground floor to the first floor, since the inflow to the first floor is not connected to the outflow stack for the ground floor.*
2.5 Effect of the Solar Stack

In a further series of experiments, we examined the effectiveness of the solar stack in enhancing the ventilation flow as a result of the absorption of incoming solar radiation and additional heating in the stack. To this end, a current was circulated through the heating wire within the stack, and the temperature of the stack recorded. Experiments in which heat loads were applied on the ground and first floor in addition to the solar stack were carried out. Again, owing to the separate flow paths through each floor, there was no recirculation of air from the ground floor to the upper floor.

![Figure 2.8 Photograph of case of heating on ground and first floors, and within the stack.](image)

In the case of additional heating in the stack (see Figure 2.8) it was observed that the flow in the stack is more vigorous, leading to a greater buoyancy-driven flow.

![Figure 2.9 Temperature as a function of time.](image)
In the experiment shown in Figure 2.9, the hot wire in the stack is turned on at a time of about 800s, and at this time it may be seen that the average temperature within the stack increases substantially, but also that the magnitude of the fluctuations in the temperature increase because hot plumes of air rise from the heated wire and mix into the oncoming flow from the two floors. As the net flow increases, the temperature within the floors decrease by 2-3 C and this is the benefit of the solar stack.

Even with the same heat load, there is a difference between the relatively cooler ground and first floor temperatures which results from the additional stack height enjoyed by the ground floor. Using the solar façade reduces this difference, as shown in the data below in which the upper floor temperature (red) becomes gradually higher than the ground floor (blue) as the heat load on both floors become increasingly large relative to the heat produced in the solar façade. However, although there is a clear benefit in the magnitude of the ventilation flow associated with the extra buoyancy from the solar façade, in order to manage the temperatures on the different floors, the control system really needs to vary the size of the apertures on a floor-by-floor basis. Under conditions of equal heat load, there should be larger openings on the first floor to compensate for the smaller head driving the flow relative to the ground floor.

Figure 2.10 Temperature as a function of time for the case of heating in the offices and within the stack.
When the heat load on each floor is smaller than the heat load in the solar stack, the flow is dominated by the solar stack and is comparable on each floor, since the buoyancy in the upper part of the stack controls the flow. With larger heat loads in the floors themselves, the greater buoyancy associated with stack as experienced by the ground floor, leads to lower temperatures on the lower floors, even though the flow path for the different floors are independent.

2.6 Wind Assisted Termination Design

A new stack termination system has been designed for the stacks to provide flexibility to optimise the benefits of wind-pressure and buoyancy in driving the natural ventilation flow. The key idea is to have outflow vents which point downwind, and inflow vents which point upwind. In this way, the pressure drop across the stack structures also helps to drive the flow (see Figure 2.11).

![Diagram showing stack termination system](image)

**Figure 2.11** Photograph of case of heating on ground and first floors, and a steady wind blowing across the building.
In the experimental model, we have built a small scale version of this double sided stack termination, in order to explore the potential for wind-assisted ventilation. The experimental tank is placed into a water flume and a current recirculates around the flume. This generates an exterior pressure gradient across the experimental tank, as an analogue of the wind. We then conducted a series of experiments to explore the potential impact of different stack designs. Three different configurations are explored to compare the effect on upward displacement ventilation through the building. First, a stack with a downwind opening; second a stack with both a downwind and an upwind opening; and third, a stack with just an upwind opening. It is seen that the additional pressure draw associated with the downwind vent leads to substantially greater ventilation, and therefore lower temperatures, than in the case in which both the upwind and downwind vents are open. This is partially because in this latter regime, the air tends to short-circuit across the stack, with some inflow on the upwind side, and there is less draw from the stack. With the upwind aperture open, and the downwind aperture closed, there is a negative pressure which tends to suppress the ventilation, leading to larger interior temperatures.

![Diagram showing temperature as a function of time for different stack configurations.](image)

*Figure 2.12 Temperature as a function of time for the case of heating in the offices and a background steady wind blowing across the building.*
Based on these experimental measurements, the detailed stack termination design has converged to a tower structure which is partitioned into 4 compartments. The four vertical compartments are arranged at different orientations around the stack, and are independently opened or closed by independent louvres. The louvres are activated by sensors which detect whether the flow is outflow or inflow, and open or close accordingly, thereby allowing outflow on the downwind side, and closing the upwind side of the stack so that the wind-assisted ventilation is optimised.

Finally, it should be noted that in Winter, a mixing mode ventilation may also be used rather than displacement ventilation. This may enable pre-heating of the incoming air by the heat generated within the offices rather than by conventional heaters, and lead to lower fuel bills during Winter – the limiting factor for transition from natural ventilation to mechanical ventilation in cold weather should be the levels of humidity required within the offices, since mechanical ventilation allows for artificial humidification of the air whereas the natural scheme does not.
3 Model Calculations of Ventilation Rates and Temperatures

The experimental models indicate that the upward displacement mode of ventilation can be very effective in ventilating the offices on the different floors of the building, especially when used in conjunction with the solar façade system, which can enhance the flow and reduce the temperatures, especially on the lower floors. The new design of parallel inflow and outflow stacks removes the challenge of recirculation of air from lower floors to the upper floors, and appears highly effective in the experiments. However, a key aspect of the design is that the size of the stack openings (inflow and outflow) are sufficient for the heat load in the space. Here we present some calculations which indicate the size of the openings which are required to achieve different ventilation rates within each floor.

![Figure 3.1 Model prediction of temperature elevation as a function of heat load for a room comprised of a specified effective area and height of warm air column.](image)

In Figure 3.1 we illustrate the temperature elevation relative to the exterior which would be expected with a heat load as shown on the horizontal axis and with inflow and outflow vents of effective joint area a as labelled on the curves. The height of the stack, h, as labelled on the curves corresponds to the height of the column of buoyant air above the room in the stack. It is seen that with purely buoyancy driven ventilation in the new inflow – outflow façade system, the temperature elevation may be controlled from values of 1 to 10°C in excess of the exterior, for the different heat loads shown.
Ventilation rates of 0.2-1.0 m$^3$/s can be achieved for most of the heat loads, effective vent areas and both ground and first floor rooms which access stacks with 2 or 4 m of stack above the room.

Ventilation rates of 10 l/s per person is equivalent to 0.01 m$^3$/s and so this is easily adequate for up to 1-10 people in an office (the number corresponding to a heat load of 200-2000 W).

The effective area of 0.25-2 m$^2$ corresponds to a composite area of the inflow vents at low level and the outflow vents at high level in the room leading into the stack, as well as the size of the aperture at the top of the stack (depending on whether it is the outflow vent from the room or the aperture at the top of the stack which controls the outflow). The figure below illustrates the relationship between the effective area and the area of the upper and lower openings in the building.
In Figures 3.1 and 3.2, the area shown is the net opening area. The model calculations assume that there is negligible pressure loss in the inflow chamber at the base of the building prior to air passing into the inflow façade; and also that the effective area of the outflow façade includes the pressure loss as air moves from the room to the façade stack and also from the stack through any termination to the exterior. If the control is at the exit from the room, then the outflow termination may not reduce the effective area significantly but if the two areas are comparable, then the pressure loss will be given by the geometric average of the two areas \((a_1^2 \cdot a_2^2 / (a_1^2 + a_2^2))\), where \(a_1\) and \(a_2\) represent the effective areas of each of the two openings, rather than being proportional to the inverse square of the smaller of the two areas.

### 3.1 Benefit of Wind

The wind assisted stack termination can lead to a substantial increase in the ventilation rate in the event of wind. For example, the typical pressure to drive the flow associated with the thermal buoyancy of the air is of order \(\rho g H \Delta T / T\), and for a temperature elevation of 1-10°C, and height of 1-10 m, this may be of order 0.03-3.0 Pa. In contrast, with a wind of 1-2 m/s, the pressure drop across a stack may be of order 1-4 Pa, which can therefore more than double the pressure driving the flow, leading to an increase in flow rates by 40% for a given setting of the opening areas. This will lead to much improved reliability of the driving force for the ventilation, and points to the importance of the control system so that in windy conditions the opening areas can be reduced thereby maintaining satisfactory ventilation levels and not overventilating the space. The optimal design for the control of the system would be a
local feedback loop, in which the temperature of the flow in the stacks is monitored and if this is too high or too small, the aperture of the openings are changed until the temperature returns to the design conditions.

### 3.2 Solar Façade

The potential benefit of the solar façade is in the additional buoyancy of the air as it is heated in the façade above the temperature of the rooms. This additional heat load can be distributed uniformly along the façade, and therefore the air rising in the façade becomes increasingly hot and buoyant. If the air is heated at a uniform rate, then the buoyancy associated with the total heat flux will be equivalent to the heat being supplied at the mid height of the façade. The typical heat load is of order 100-500 W/m² depending on the season and aspect of the façade. Over a height of 4m, a 1m wide façade would therefore provide an additional heat load of 400-2000 W. The fraction of this heat load which is transferred to the air flow depends on the balance between (i) the conductive and radiative losses across the outer skin of the façade; (ii) the time-constant associated with the heat conduction into the façade material, which will increase as the thermal mass of the skin increases; and (iii) the speed of the air passing the heat absorbing material in the façade, which controls the rate of convective heat transfer to the air. Detailed specifications of the glass, the insulation and the radiative properties of the heat absorbing material are required to calculate this partitioning of the incoming solar gains; we have therefore included some figures to illustrate the benefit of the additional heat load as a function of the additional solar heating (see below), with the additional heating lying in the range 0-2000 W.

![Figure 3.4 Increase in ventilation rate owing to heating in façade.](image)
Figure 3.5 Reduction in temperature elevation resulting from increased flow in heated solar façade.

The figures above illustrate the potential for the additional solar heating of air rising through the outflow stack to provide additional ventilation flow and hence lower interior temperatures in conditions in which the interior is warmer than the exterior and upflow displacement ventilation is used.

There are two further design issues which needs to be considered in the solar façade, relating to 1) the fact that the building will be mechanically ventilated for some of the year and 2) the reduction in efficiency of PV cells with temperature. These issues have been discussed with Short & Associates and the other engineers on the project.

1) During high Summer, a mechanical system will be used when the outside humidity reaches sufficiently high levels that removal of moisture is necessary. However, the mechanical system may also be used during Winter, when the humidity levels are too low. In this case, the system will capture some of the heat energy from the exhaust air in order to improve the efficiency of the mechanical system. If the solar façade is to provide the exit pathway for both the natural and mechanical ventilation system, then the façade should be well insulated in order to reap the benefits of the heat recovery system. However, if the façade is well insulated, then the solar heating of the air in the façade is likely to be less than in the case of a simple glass-walled exterior panel. This conflict could be resolved by dividing the exit pathway into two, with the outer pathway for use by the natural ventilation system and a well insulated inner pathway for use by the mechanical system.

2) The solar façade could be heated by PV cells lining one of the inner walls. However, if the PV cells are located behind an outer glass screen, the amount
of solar radiation reaching the PV cells will be reduced. Furthermore, it is intended that the temperature of the air in the solar façade is greater than that outside, and so the conversion efficiency of the PV cells is also reduced. It might therefore be appropriate to consider lining the inner wall of the façade with a simple passive, radiation-absorbing material to provide the solar heating to the air, and locating the PV cells on a different external surface in a conventional way to provide electricity. Although this would require further material for the building, it would help maximise the benefits of the PV cells.

3.3 Seasonal Variations

In this report, we have focussed on upflow displacement ventilation, which is the preferred mode of ventilation for the shoulder seasons, in which the exterior temperature is below the design temperature within the library/office building. However, as the exterior temperatures increase above the design temperature for the interior of the building, upflow displacement ventilation becomes more difficult in a purely buoyancy driven natural ventilation regime. Instead, relatively cool air within the building tends to descend under gravity and so the upward displacement mode is not possible, although in windy conditions a wind-driven upward flow may dominate the downward force of gravity and thereby lead to upward displacement ventilation; note that in neutral, wind-free conditions, this is not possible.

Several different solutions are possible in such conditions, if these occur prior to the transition to use of the parallel mechanical conditioning system which is being installed for humid summer use and potentially very dry winter months. First, since the air entering the building may be pre-cooled through the large thermal mass installed at the base of the building, the benefit of the thermal mass could be realised through use of low-wattage fans in the outflow stacks to draw air through the pre-cooled chamber and force the ventilation; although this is not a fully natural system, it may provide a solution for the small number of days in which conditions are unseasonally warm, without the need to revert to the full a/c system. Furthermore, the additional heating in the solar façade would also help overcome the negative buoyancy. In addition, the installation of such fans would enhance the potential for night cooling of the building, providing a back up to the natural system driving the pre-cooling.

Second, a downward displacement ventilation regime could be used, in which inflow occurs at high level while air descends through the space, and vents at low level from the building; this would be run in minimum ventilation mode so as to minimise the ingress of warm air into the building, and allow the thermal mass within the space to buffer the interior temperature by absorbing a substantial fraction of the internal heat load. This solution would require either pre-cooling equipment (e.g. cold water pipes) or thermal mass at high level.
4 Conclusions

In this report, we have described two new natural ventilation systems which have been developed for application to the new library development at Judson College.

First, we have developed a model of the flow in a double façade system, with parallel inflow and outflow stacks. We have developed a model of the ventilation efficiency in this double stack design, and built a small-scale analogue laboratory model which confirms that the design should prevent the occurrence of recycling air from the lower floor to the upper floor. It also illustrates the benefits of a solar façade which absorbs radiation and thereby enhances the ventilation flow by 10-50% depending on the internal heat load.

Second, we have described a novel stack termination system, which has been developed for the project in order to optimise the effectiveness of the natural ventilation under both wind and buoyancy driven regimes. A small-scale analogue model of the stack system has illustrated the benefits of the additional draw of a downwind stack in increasing the ventilation flow rate, and thereby lowering the temperature in the occupied space.

Both of the new designs have been developed for the challenging and novel application of natural ventilation in the Chicago area climate. They also allow for effective use of natural driving forces for the flow in a way that is sympathetic to the architecture of the Judson Campus, through the new stack termination system.