MegaFan Case Study: Final Report

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Overview

Researchers from the University of Liverpool's Engineering Department have been contracted by MegaFan Technologies Ltd (MTL) to model the airflow and heat transfer in a heated warehouse building to investigate the levels of de-stratification offered by high-volume, low-speed (HVLS) fans. Computational Fluid Dynamics (CFD) has been used to develop a model of a generic warehouse building that includes a HVLS fan, as well as an air heater. Heater power requirement estimates have been derived based on a target ground level temperature of 16°C; this has been performed for both 'fan on' and 'fan off' conditions. Several different building heights and outside temperatures have been studied to obtain performance metrics for the HVLS fans in a variety of operating conditions. For the case of an outside temperature of 4°C, the analysis has indicated heating power savings of between 40 and 45% when the HVLS fan is deployed.

Scope

The scope of this study was as follows:

- Create a computational model of a generic warehouse building having a footprint of 30x30m; with apex heights of 12.5m, 15.0m, 17.5m and 20.0m.
- Implement fan downwash and heater components into the model to account for the effects of heat, mass and momentum transfer due to the heater and HVLS fan.
- Determine the heater power required to produce a ground temperature of 16°C for all building heights with HVLS fan on and off (for an outside temperature of 4°C).
- Determine the heater power required to produce a ground temperature of 16°C for the 17.5m building for outside temperatures of -4°C and 0°C.
- Derive estimates of energy savings due to the use of the HVLS fan.

The work reported here follows an earlier feasibility study carried out by the current authors (report dated 15th March 2010), which showed that results from the stratification/de-stratification model agreed well with anecdotal evidence from existing HVLS users.

Background

Thermal stratification occurs in heated buildings due to the natural buoyancy of warm air, causing heated air to rise and gather at the ceiling. This leads to thermal inhomogeneity characterised by layering, with temperatures typically increasing by 0.5°C to 1°C per metre (floor to ceiling) in the vertical direction. Thermal stratification is most severe in buildings with high-ceilinged rooms which are heated from above, such as warehouses, where the effect causes energy wastage due to the fact that most of the room (above the height of the thermostat) is heated to a higher temperature than the thermostat set-point.

HVLS fans are typically located close to the roof and provide thermal de-stratification by pushing the warm air down towards the ground. This creates convection currents and also encourages mixing between the warm and cold air, leading to a more uniform temperature distribution and less energy wastage.

Anecdotal evidence from existing HVLS users has indicated that, following the installation of the fans, substantial energy savings have been made through the winter months, leading to a reduction in heating bills. Although the way in which these fans work is fairly well understood, very little in the way of scientific research has been carried out to corroborate these in-situ findings. As a first step towards gaining a better understanding of the physical mechanisms at work, this report provides details of a computational study of heat and fluid flow within a generic warehouse building with a single heater and HVLS fan installed.

Modelling Methodology

Geometry and boundary conditions

The model has been set up such that only a single, repeatable sub-zone of a warehouse is modelled, shown in Fig. 1. This simplification significantly reduces the model run-time, as modelling a full warehouse with multiple heaters and fans using current computational hardware was unfeasible in the project time-scale. The geometry was designed such that the height of the apex could be varied from 12.5m to 20m, with the fan mounted approximately 1m below the apex. The heater was placed towards one side of the domain, located approximately 2m below the roof; this layout was based on a warehouse schematic provided by MTL.

Losses through the ground, roof and vertical walls were modelled assuming only convective heat transfer, with heat flux given by:

$$q = U(T_{ext} - T_w)$$

where U is the heat transfer coefficient (U value), T_{ext} is the external (outside) temperature and T_w is the temperature at the wall (calculated by the solver). The U values for the ground, vertical walls and roof were set to 0.5, 0.25 and 0.485 W/m^{2}K, respectively.

The two vertical walls farthest from the heater were set as symmetry planes, allowing the domain to be reflected about the x and y axes; this effectively modelled a geometry four times as large. All other faces were set as walls with a no-slip condition.

Computational method

The warehouse model is represented by approximately 2.8 million computational cells, which are clustered tightly around regions of interest (e.g. fan, heater). The equations of fluid motion and heat transfer are solved iteratively at each cell, ensuring that mass, momentum and energy conservation laws are obeyed. At the start of the computations the velocity in the domain is set to zero and the temperature is set to equal the outside temperature. This effectively simulates the gradual heating up of the warehouse building. Once the iterations have converged to a steady solution, the final outputs are the resulting velocity, pressure and temperature fields.

A pressure-based Navier-Stokes solver was employed for the computations, with second order accurate upwind discretisation used for the convective terms and the SIMPLEC method used for pressure-velocity coupling. In order to simplify the computations and aid convergence, the Boussinesq approximation was used. Therefore, air density was fixed constant in all equations except the for the buoyancy term in the momentum equation. Convergence to steady state was achieved after approximately 50,000 iterations in all cases.

To account for the effects of turbulence, the standard k-ε model was employed, augmented with enhanced wall functions and buoyancy effects. To ensure that convective heat transfer at the walls was accurately modelled, it was crucial that the viscous boundary layers were resolved; therefore the computational mesh was designed to give y^+ values between 1 to 5, placing the first cell centroid within the viscous sub-layer.

Component modelling

The heater is based on an AmbiRad USDA 100 room heater, which operates at a maximum heat output of 97 kW and air flow rate of 10,360 m^3/h. For the purposes of this study, the heater flow rate was kept constant at approximately 9,000 m^3/h, and the heat output was varied as required. Heat was introduced to the warehouse using an energy source located within the heater, which was fed with air from the surroundings using a simplified fan model consisting of an instantaneous pressure jump of 50 Pa (also located within the heater body).

The HVLS fan model was developed based on aerodynamic data (lift, drag and pitching moment coefficients) computed from a two-dimensional section of a MegaFan fan blade using CFD; Fig. 2 shows the structured mesh used to compute the aerodynamic data. Data for a total of 50 angles of attack were obtained, with the resulting aerodynamic coefficients shown in Fig. 3. Also shown in Fig. 3 are the corresponding coefficients for a NACA 0012 aerofoil, which is similar in shape and, therefore, has similar aerodynamic characteristics, thereby giving confidence in the values assigned to the MegaFan blades. Figure 4 shows an example of pressure and velocity magnitude contours over the MegaFan aerofoil from a computation with an angle of attack of 8°.

Downwash is calculated using 'blade-element theory', in which each blade is split up into sub-sections. The volume of air that a blade section forces downwards is directly related to the amount of lift it produces, so the lift on each section is calculated based on the local air velocity. The overall effect on the flow field is a source of momentum which pushes air down towards the ground.

The fan itself is based on a 10-blade MegaFan MaxAir fan, with a diameter of 7.3m. For the computations the rotational speed was set to approximately 36 RPM, corresponding to 55% of the fan's full speed. Blade pitch angles were fixed at 7°; this was based on the mean chord angle from leading to trailing edge on the actual aerofoil section.

Modelling approach
The approach taken during the current study was to determine the heater power setting that was needed to attain an average temperature of 16°C at a height of 1.5 m above the ground (for both HVLS fan on and off cases). This temperature was chosen is it represented a typical working temperature in the warehouses of current HVLS fan users. For the remainder of the report the average temperature at 1.5m above the ground will be referred to as 'ground temperature'.

To determine the required heater power for each combination of apex height, outside temperature and fan state it was necessary to run several computations for each combination, varying heater power each time. Once enough data points had been gathered for a particular case (typically between 4 and 6 points), a best-fit curve of the form $y = Ax^B + C$ was plotted through the points to provide an estimate of ground temperature as a function of heater power (see Fig. 5). From these plots it was then possible to read across for the heater power needed to achieve 16°C at the ground.

Having determined the difference in heater power requirements between fan-on and fan-off cases, the energy savings offered by the HVLS fan can then be calculated based on the power reduction compared to the fan-off case. For example, considering the data shown in Fig. 5, to achieve the 16°C ground temperature, the heater power required with the fan on is 13 kW, compared with 19 kW with the fan off; a saving in heater power of approximately 30%.

Modelling assumptions
It should be noted that this computational study involves several modelling assumptions and simplifications. It was not feasible, nor indeed possible, within the current project timescale to account for all thermal gains and losses to and from the building, such as solar loads, lighting, doors, air leakage etc. Similarly, the warehouse is modelled empty with no racking, people or furniture.

To further improve confidence in the presented results, it would be beneficial to validate the model against velocity and temperature measurements taken in a real warehouse; as well as comparing predicted levels of power consumption to those recorded. Unfortunately no such data is currently available, so the results predicted by the model must be interpreted with care. However, levels of energy saving predicted from initial studies showed encouraging agreement with those reported by existing HVLS fan users.

Cases Studied

Each test case was run twice; once with the HVLS fan on and again with the fan off. The cases which were modelled during this study are as follows:

- Testing the effect of warehouse height
  - Outside temperature of 4°C (UK average winter temperature as stated by the Met Office)
  - Apex heights of 12.5m, 15.0m, 17.5m and 20.0m.
- Testing the effect of outside temperature
  - Outside temperature of -4°C, 0°C and 4°C
  - Apex height of 17.5m

Results

Thermal stratification was observed in all cases with the fan off; conversely, all fan-on cases exhibited complete de-stratification. Figure 6 shows contours of temperature through the warehouse domains, indicating that, with the fan off, levels of stratification are similar for the different warehouse heights, at between 0.5°C and 1°C per metre. A uniform temperature distribution can be seen in all of the fan-on cases.

Figure 7 shows contours of velocity magnitude through the warehouse domains, highlighting the effects of the heater and HVLS fan; these are the main convective mechanisms driving the flow. In both the fan-off and fan-on cases, air flowing from the heater can be seen to rise slightly due to buoyancy effects and travel along the roof as far as the opposite wall. At the wall the flow is forced downwards for a short while, before a combination of dissipative losses and buoyancy forces combine to retard the flow. The most obvious difference between the fan-off and fan-on cases is the downwash from the HVLS fan in the fan-on cases, which reaches velocities of almost 2 m/s. A spreading wall jet can be seen at the floor; the flow here also reaches the side walls and is forced upwards towards the roof. The fact that air is also drawn in to the top of the HVLS fan helps to maintain flow circulation around the warehouse. This re-circulating flow is shown clearly in Fig. 8, where streamlines indicate the path of fluid particles from the HVLS fan downwash.

Figure 9 shows that the required heater power increases with increasing apex height. This is to be expected, as a higher roof means a larger volume of air to heat and a greater wall area from which energy is lost. It is also clear that significantly less power is required with the HVLS fan operational. With the fan off, much of the energy from the heater is used to heat air which remains near the roof at a much higher temperature than is required at the ground; this is wasted energy. In contrast, with the fan on, the warehouse is uniformly heated and no heat energy is wasted heating the upper part of the room.

It is interesting to note that the fan-off cases exhibit non-linear behaviour in terms of the variation of power with apex height. A marked increase in required heater power can be seen between 12.5m and 15.0m; however this increase is not so dramatic at higher apex heights. This is because stratification is not so severe at lower roof heights due to the proximity of the warm upper layers to the ground and also the influence of the heater jet bringing warm air down the side wall; therefore, for the 12.5m height, less heater power is needed with the fan off because some air circulation is provided by the heater. As the building height increases, the influence of the heater jet on the near-ground region diminishes.

The results shown in Fig. 9 can be translated into energy savings, both in terms of absolute values and percentage savings compared to no HVLS fan; these are shown in Fig. 10. It can be seen that, for the 4°C outside temperature cases, power savings increase up to a point between an apex height of 15.0m and 17.5m, before reaching a plateau. This does not indicate that the HVLS fan is less effective at lower warehouse heights; rather that stratification is less of a problem at these heights, as discussed previously. The model results show that the percentage energy savings offered by the HVLS fan are between 40% and 45% for apex heights between 15.0m and 20.0m.

Data presented in Figs. 9 and 10 also show the effect of outside temperature on heating power requirements; this is shown more clearly in Fig. 11 where it can be seen that, for both fan-off and fan-on cases, there is a steady increase in required heater power with decreasing outside temperature. Although the percentage energy savings only show a modest increase as outside temperature drops, the absolute power savings double when the temperature falls from 4°C to -4°C. This corresponds to a saving of between 1 and 1.5kW per degree the temperature falls below 4°C. Although the curves in Fig. 11 appear linear, this is not the case since both curves must converge to a power of 0kW at 16°C. The deviation of the curves from each other as outside temperature decreases suggests that power savings from the HVLS fan would continue to increase with falling temperature.

Conclusions

A computational model of a generic heated warehouse building has been developed, in which heat transfer and fluid flow has been modelled to investigate the efficacy of HVLS fans. In cases with the fans not operational, natural thermal stratification has been observed; the ability of the HVLS fans to de-stratify the warehouse building has been clearly demonstrated.

For the cases studied, energy savings offered by the HVLS fans for an outside temperature of 4°C were seen to peak at between 40% and 45%. Additional savings were observed as outside temperature was reduced. It was found that maximum benefit from the fans could be gained for warehouse heights above 15.0m, although even at a height of 12.5m the level of energy saving was approximately 32%.

The model has demonstrated that the HVLS fan is effective due to convective mass and heat transfer, shifting large volumes of air from the upper part of the warehouse to the ground. This sets up air currents which also encourage mixing, leading to complete de-stratification of the warehouse.

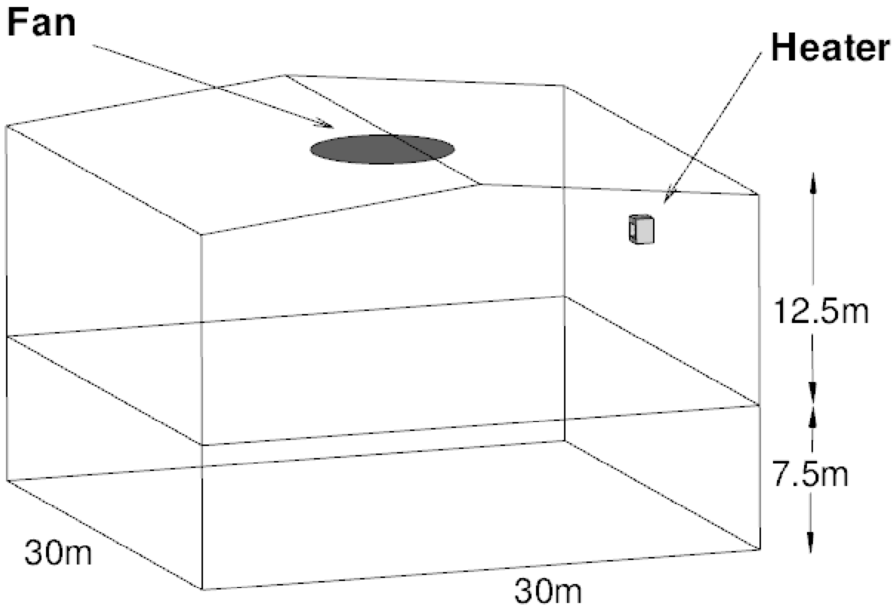
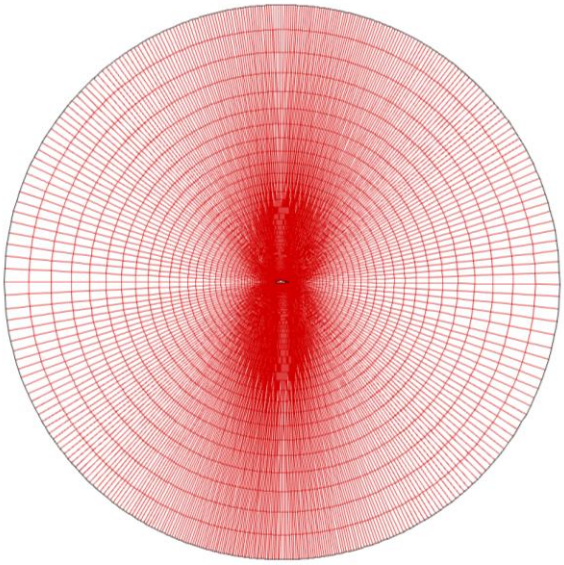
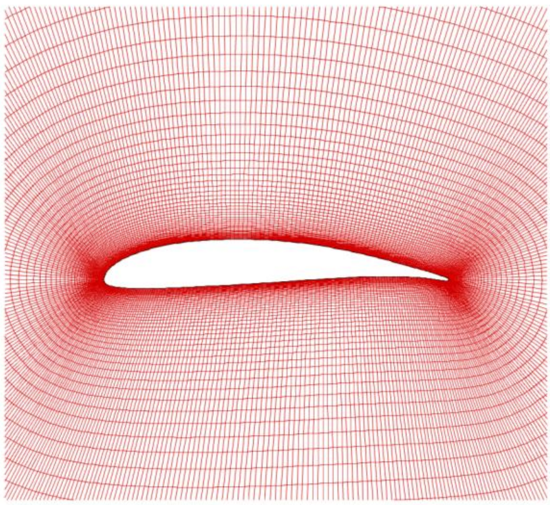


Figure 1: The warehouse model geometry (roof apex can be varied from between 12.5m to 20m above ground level).



(a)



(b)

Figure 2: Computational mesh used to calculate MegaFan blade aerodynamics. Complete mesh (a); close-up of blade profile (b).

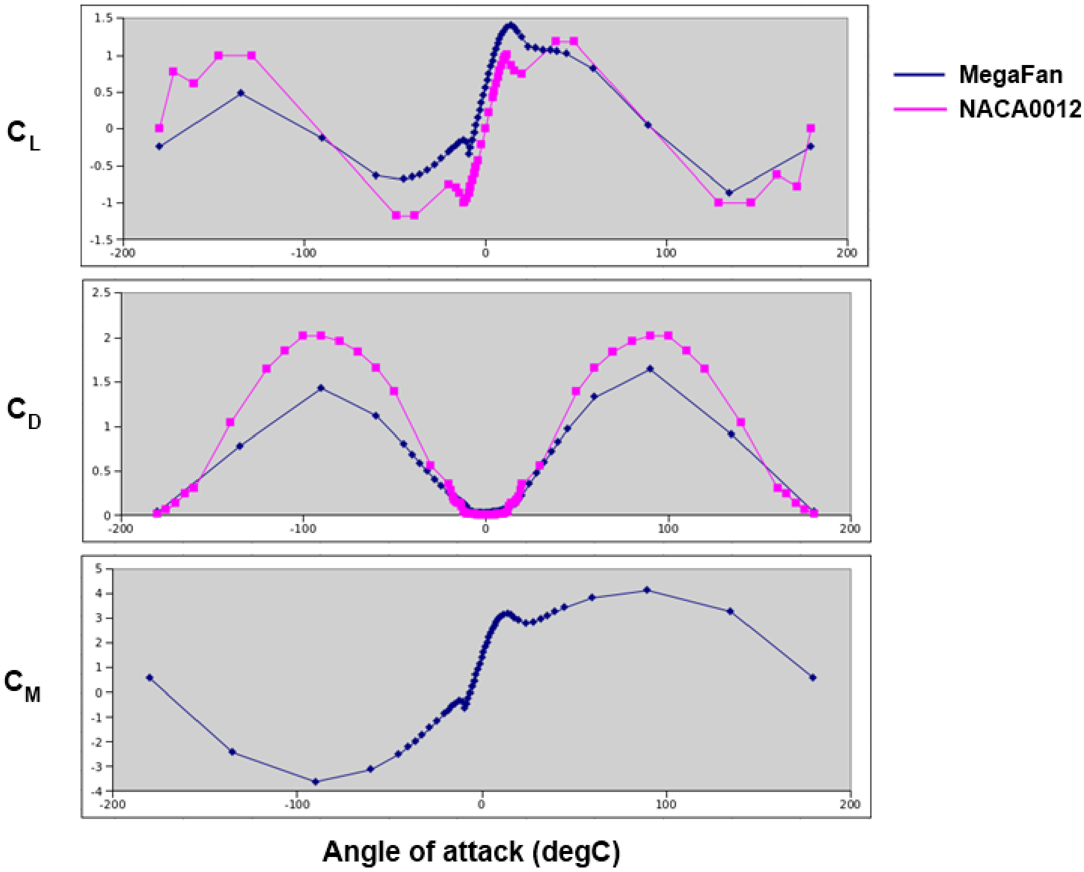
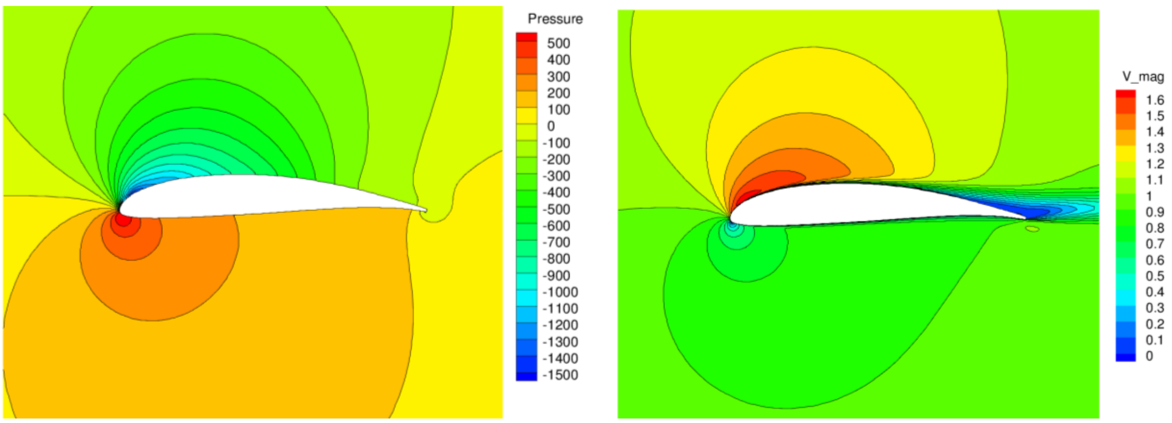


Figure 3: Aerodynamic coefficients for the MegaFan blade aerofoil as computed by CFD. Results for a NACA0012 aerofoil also shown for reference.



(a) (b)

Figure 4: Pressure (a) and velocity magnitude (b) contours over a section of MegaFan HVLS fan blade at an angle of attack α = 8°.

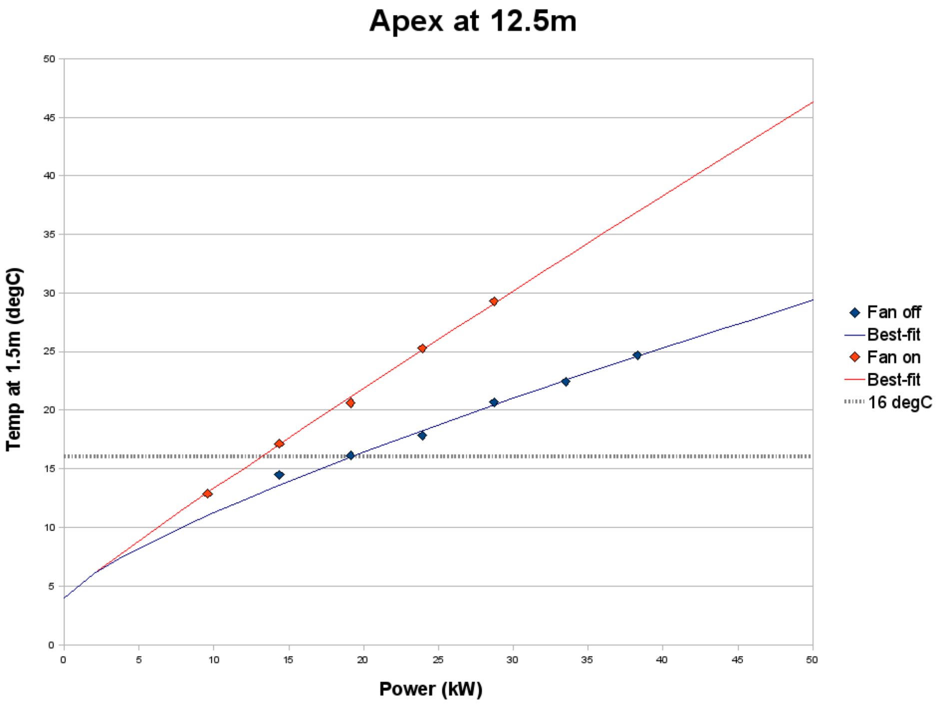
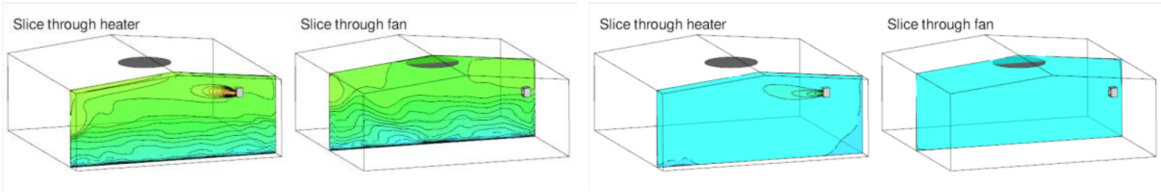


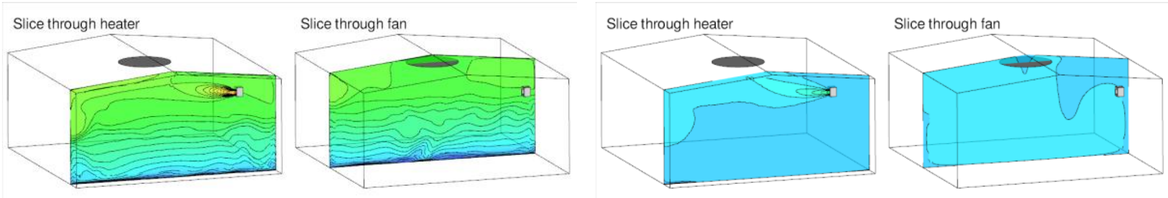
Figure 5: "Ground temperature" as a function of heater power for the 12.5m apex case. Curves are shown for both fan-on and fan-off cases, with the dashed line indicating 16°C.

Fan off (heater at 29.1 kW) **Fan on (heater at 14.6 kW)**

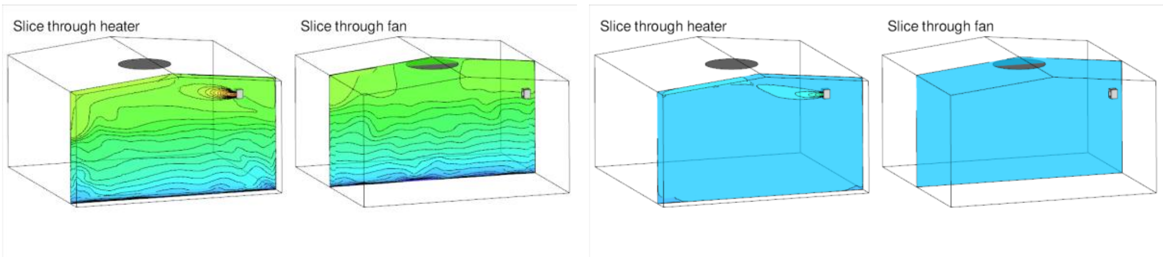
(a)



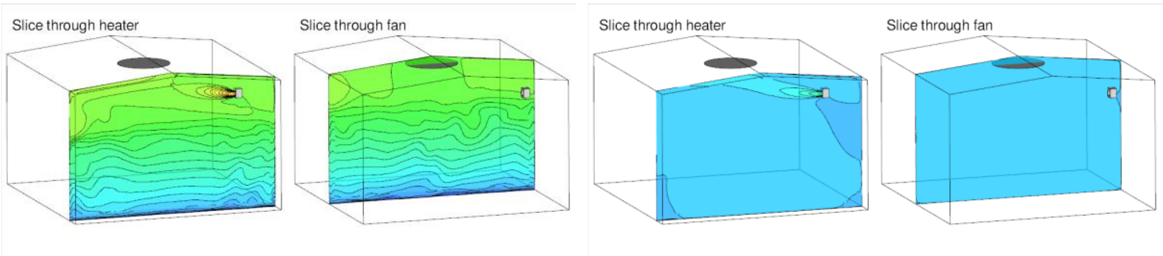
(b)



(c)



(d)



Temperature (°C)

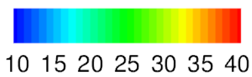


Figure 6: Contours of temperature plotted on slices through the warehouse domain for the fan-off case (left) and fan-on case (right). Apex heights of 12.5m (a), 15.0m (b), 17.5m (c) and 20.0m (d). Outside temperature 4°C.

Fan off (heater at 29.1 kW) **Fan on (heater at 14.6 kW)**

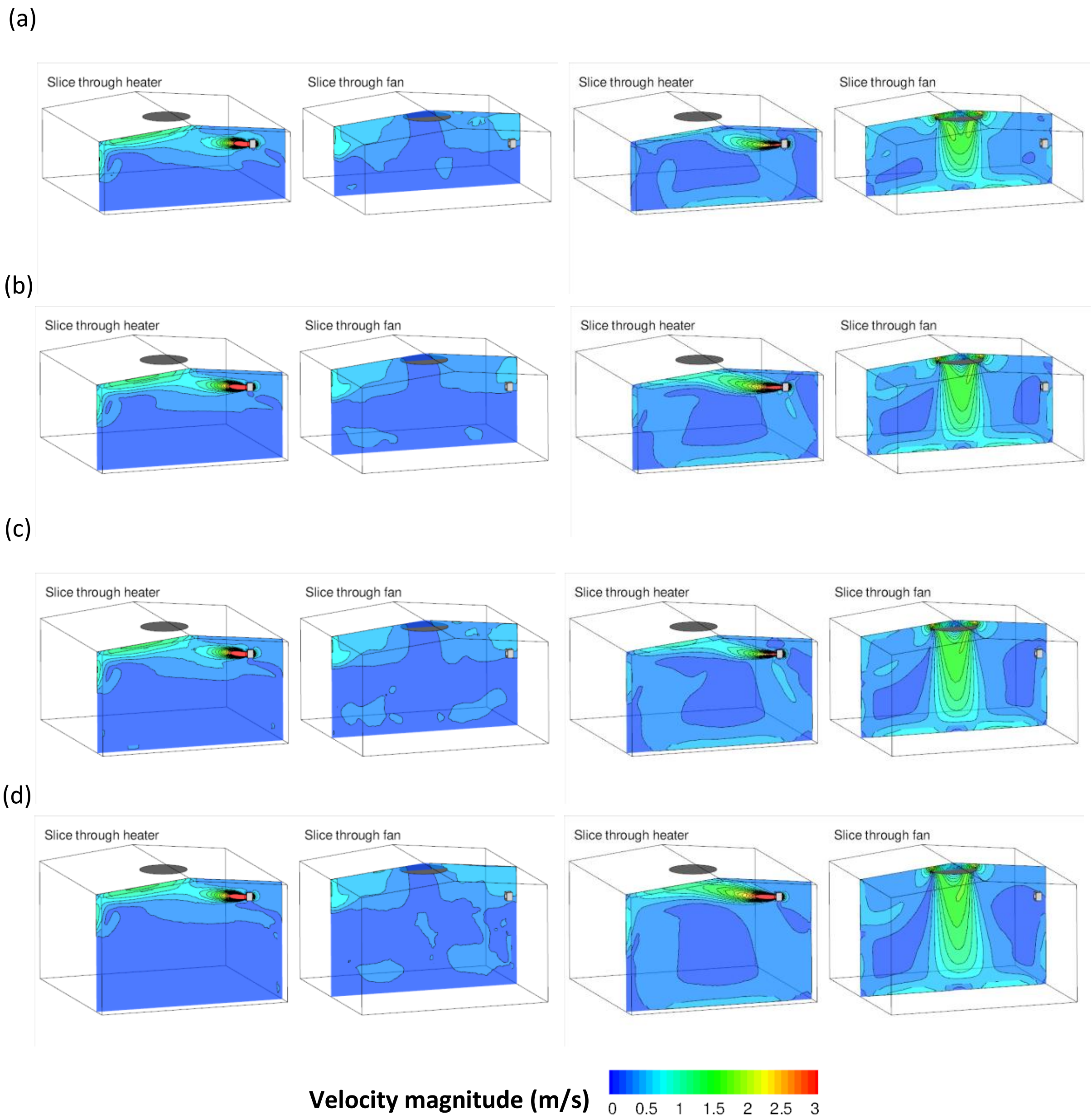


Figure 7: Contours of velocity magnitude plotted on slices through the warehouse domain for the fan-off case (left) and fan-on case (right). Apex heights of 12.5m (a), 15.0m (b), 17.5m (c) and 20.0m (d). Outside temperature 4°C.

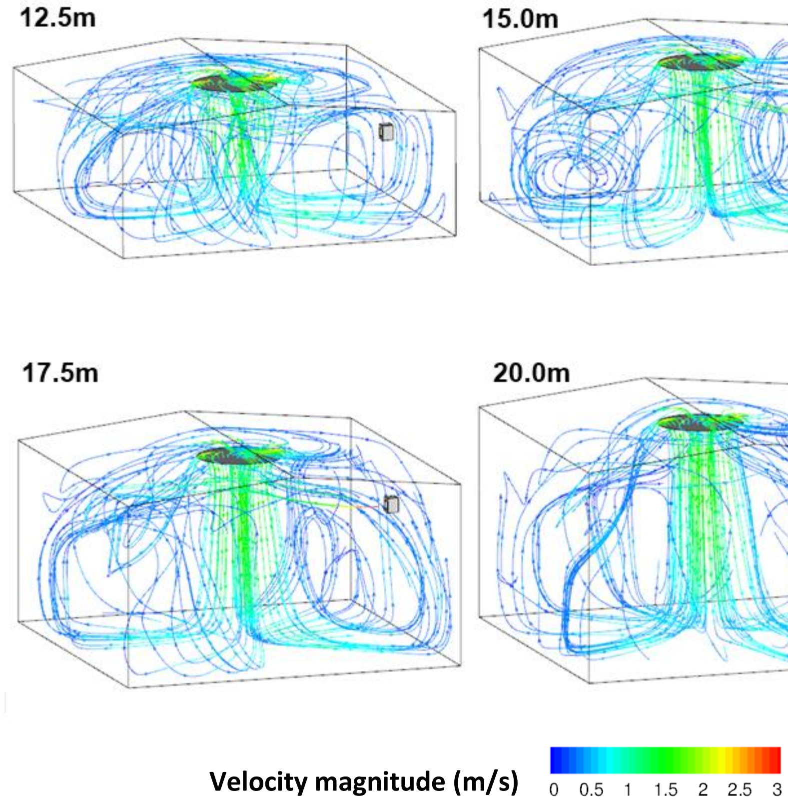


Figure 8: Streamlines showing HVLS fan downwash for the four warehouse heights, coloured by velocity magnitude.

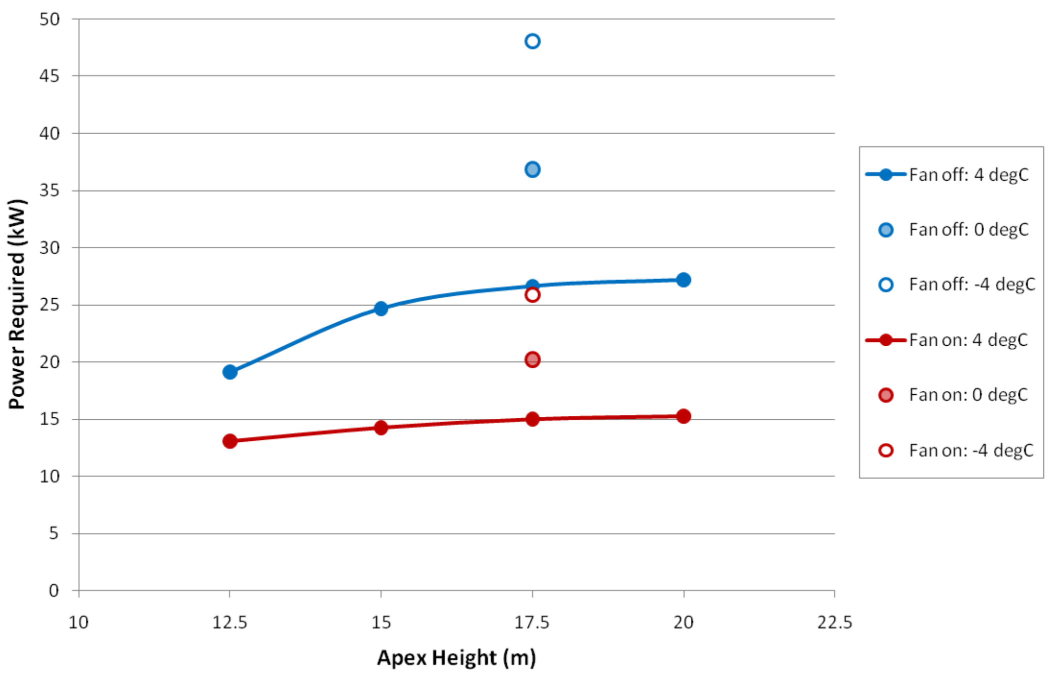
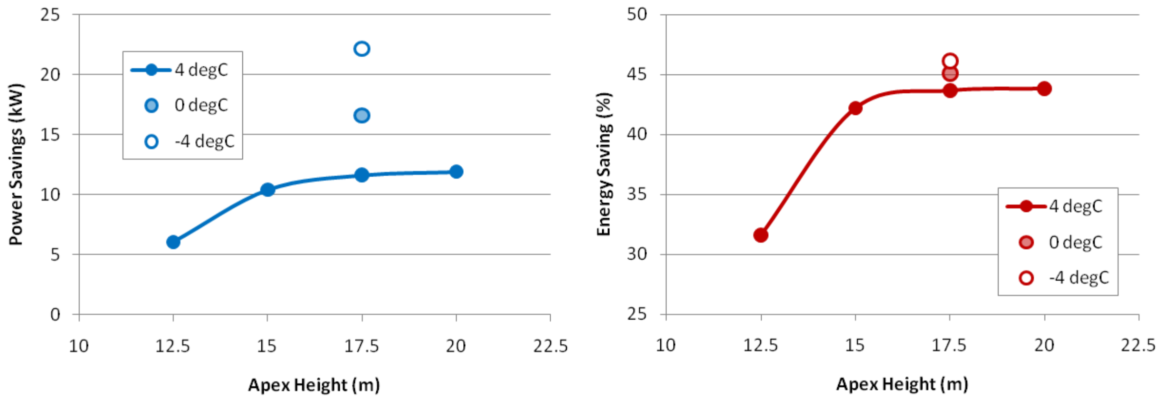


Figure 9: Graph showing heater power required to achieve an average ground temperature of 16°C, as a function of apex height and outside temperature.



(a) (b)

Figure 10: Graphs of absolute power savings (a) and percentage energy savings (b) provided by the HVLS fan as a function of apex height and outside temperature.

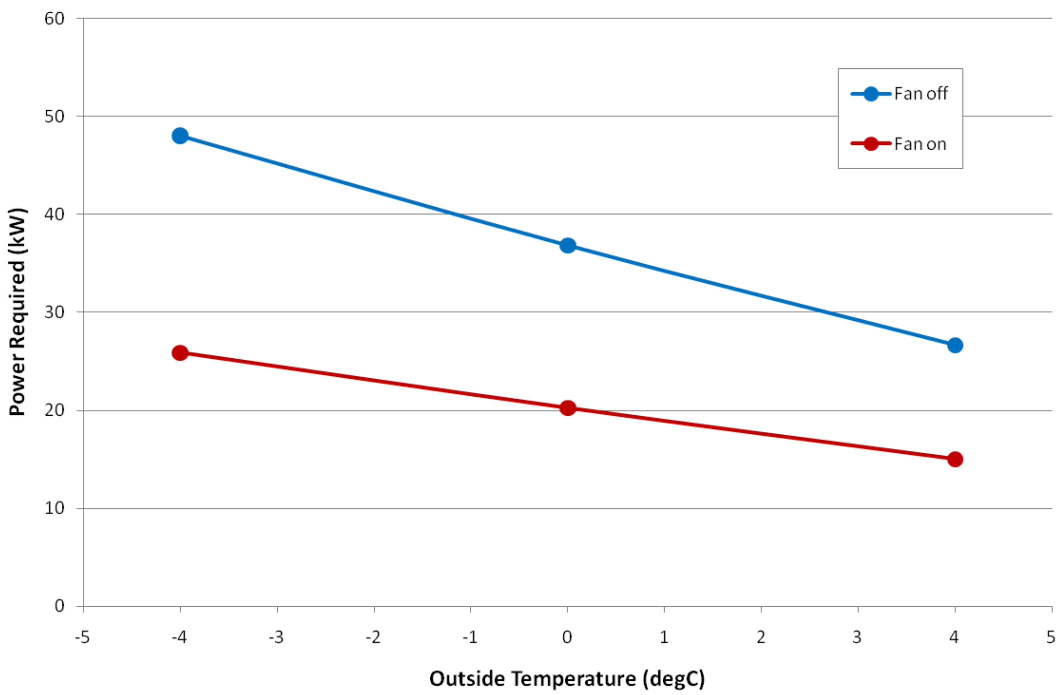


Figure 11: Graph showing heater power required to achieve an average ground temperature of 16°C for a 17.5m apex, as a function of outside temperature.