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RESULTS OF PHASE 2 THERMAL FLOW MODELLING WORK FOR THE CELSIUS PROJECT

LOUISE WRIGHT

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Louise Wright
Data Science Group

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National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

Approved on behalf of NPLML by
Alistair Forbes, Science Area Leader, Data Science.

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1 SCOPE OF THE DOCUMENT

This report is a deliverable of Phase 2 of the thermal flow study that forms NPL's contribution to the Celsius project. The Celsius project aims to use measurement and modelling to assess the thermal performance of assets, including substations and the transformers inside them. This assessment will enable network managers to ensure their infrastructure is able to meet future anticipated rises in demand without thermal damage occurring. The models reported here focus on cooling of transformers that are situated within buildings, with a focus on the specifications used by ENWL for new buildings.

The report reproduces the agreed specification for the work (section 2), discusses some of the assumptions and approximations used in the work (section 3), describes the alterations made to the buildings (section 4), and presents the preliminary results (section 5) and some conclusions and recommendations (section 6).

2 MODEL SPECIFICATION

This section reproduces the specification of the models to be run as agreed with ENWL and Ricardo. Some additional assumptions and approximations have been made during model development; these adjustments are explained and justified in section 3.

Note that the limited space in the GRP building has meant that it was not possible to define a "loose" and a "tight" specification that were significantly different from one another (see section 3 for details) so only the "tight" specification has been considered.

Finally, as is discussed in the results section, an error in the model development has meant that the range of air temperatures given in this specification is not what was used in the majority of the models. An error in defining the air temperature function meant that instead of varying between 12 °C and 21 °C, the temperature varied between 7.5 °C and 25.5 °C. An extra set of model runs has been carried out to examine the effects of this error.

2.1 AGREED SPECIFICATION

It is assumed that the reader has access to the report "Celsius project thermal modelling phase 1: Modelling the heat flow in transformer substations", NPL Report ENG66 [1]. This report documented the initial modelling of the heat and air flow within substations and identified a set of recommendations based on the results of that modelling. The recommendations were based on models of six substations of various types under various circumstances.

ENWL have requested that a similar set of recommendations be developed to guide best practice in new build transformer substations. This document provides a specification of the work required to develop these guidelines. The results of the work will also support the retrofitting work that will take place in April-July 2018, and additional models will be run to address the challenges associated with non-standard buildings.

The initial results of the work will be delivered by 31st March 2018 as an informal report to address proposed recommendations and associated evidence. This deadline is imposed to ensure that the recommendations can be followed during the retrofitting campaign, so the delivered results will be focussed on developing recommendations for new build and applying them to non-standard buildings. A further formal report will be delivered by 31st May 2018 that will fully specify all models and assumptions made, and may contain results of other possible scenarios if resource permits. There may be additional subsequent work after the retrofitting to assess the validity of the models used.

The following sections specify the geometry to be used, the weather conditions and transformer states to be considered, and the quantities to be varied as part of the study. Any quantity not explicitly stated to vary will be regarded as fixed, so for instance the dimensions of the buildings will not be varied. A list of models to be run is included in the final section.

All models will use the same governing equations as were used in the previous report: air flow will be treated as laminar; the density, thermal conductivity, specific heat capacity, and viscosity of air will be regarded as temperature-dependent using equations (8)-(11) of the previous report, and heat transfer coefficients will be defined as 3.6 W m^{-2} K^{-1} for the walls and floor as per section 3.4.6 of the previous report.

In order to ensure that the effects of solar radiation are captured correctly, transient models will be used rather than static ones. This approach will require redefinition of the boundary conditions to take the thermal mass of the building into account. This redevelopment will be the first step of the second phase of the project.

The models will be compared using temperature distributions, peak temperature within the building, energy leaving the building through the walls, ceiling, floor and louvres, and amount of energy removed from the transformer.

2.1.1 Geometry

Two building geometries will be used for the majority of the work, based on the current new build specification for GRP and brick transformer substations. These specifications are given in documents supplied by ENWL. The critical details are listed in table 1 below.

Table 1: Building dimensions for the brick and GRP new build specifications. Width is the horizontal dimension of the wall containing the door. GRP wall thickness estimated from existing builds.

	Brick	GRP
Internal width (m)	3.64	3.10
Internal length (m)	3.19	3.20
Internal height (m)	2.67	2.44
Wall thickness (mm)	280	40.0

The internal roof will be taken to be flat. The louvre geometry will be based on the documents supplied by ENWL, but the louvre orientation may be altered in some models to investigate the effects on the airflow.

The internal geometry of both substations will be taken to contain a transformer and two cabinets (containing low voltage switchgear (LV) and a ring main unit (RMU). The transformer and cabinet dimensions from Town Bridge substation will be used in all cases. The cabinet and transformer dimensions are specified in table 2, and figure 1 gives a sketch of the transformer geometry.

Table 2: Cabinet dimensions for the GRP build. Width is the dimension parallel to the orientation of the doors.

	LV cabinet	RMU cabinet	Main transformer body
Length (m)	0.55	0.74	1.3
Width (m)	0.98	0.56	0.46
Height (m)	1.75	1.75	1.56
Fin volume (m^3)	-	-	0.70

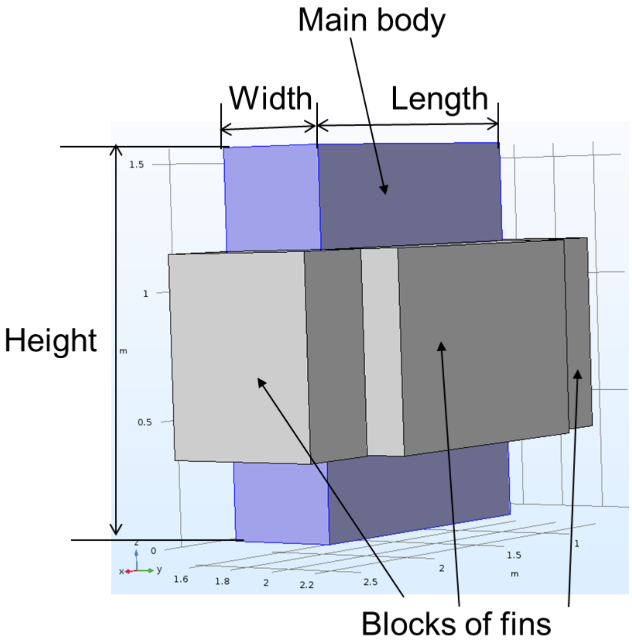

Figure 1: Transformer geometry

Two sets of locations will be defined for the plant within the building: one labelled as "tight" and one labelled as "spaced". The tight specification will place the plant close together in the centre of the building, and the spaced configuration will separate the plant items as far as possible. In both cases the configuration will be consistent with the safety constraints on the plant, which are i) that an escape route 1 m wide must be available, and ii) that all plant must be at least 60 cm from a wall. These specifications will be developed by NPL and agreed with ENWL.

Two additional buildings will be modelled to assess the effect of the proposed recommendations on cooling in non-standard build substations. The two buildings chosen are Acorn Street, which has a dividing wall in it, and Portland Grove which has a wooden partition and small louvres. The layout of these buildings is shown in figures 2 and 3.

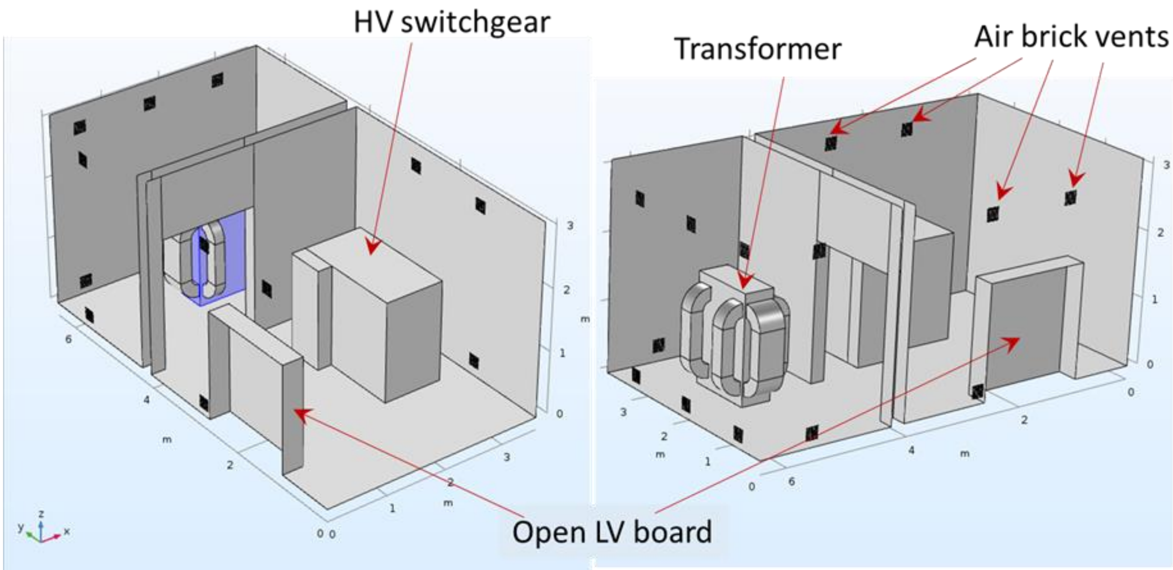

Figure 2: Internal layout of Acorn Street from two angles.

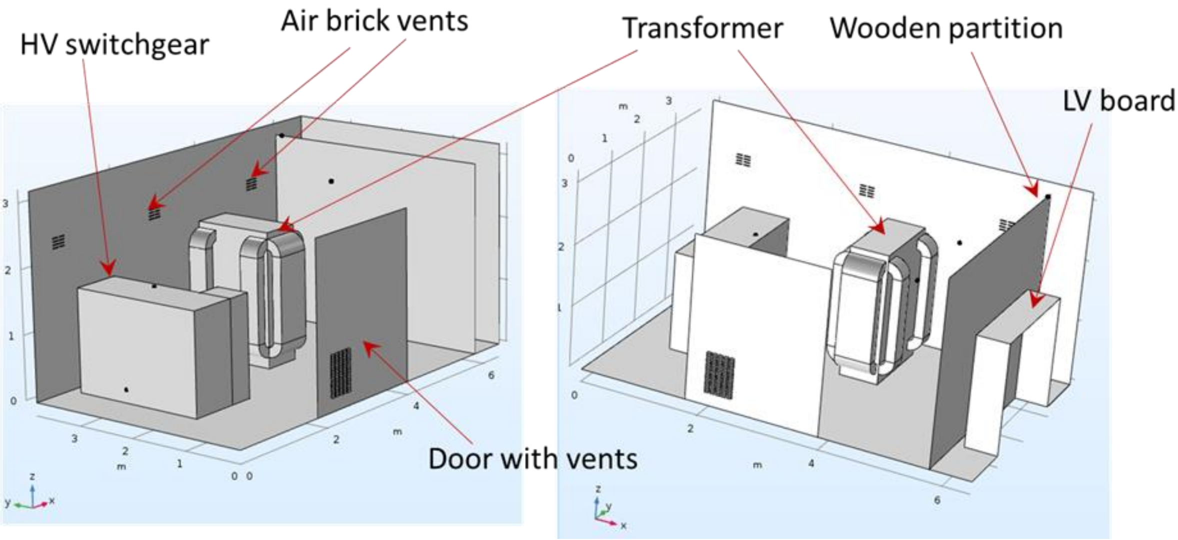

Figure 3: Internal layout of Portland Grove from two angles.

2.1.2 Weather conditions & transformer state

The models will simulate challenging conditions that a substation is likely to encounter.

The air temperature and solar radiation will be obtained from weather data. The CIBSE environmental design guide [2] gives mean values for solar irradiation in Manchester in each month. The maximum of these values (the June value of 4878 W h m^{-2}) will be used. The amount of this irradiation that is absorbed by a wall or ceiling will depend on the emissivity of the surface. Emissivity is a dimensionless value between 0 and 1, where 1 represents a perfectly black surface that absorbs all energy. A value of 1 will be used, because the irradiation data being used is a mean not a worst case value, so allowing all of it to be absorbed will lead to more heating than would typically be expected. The irradiance will be multiplied by a time-dependent function to capture the way sun intensity varies as the sun moves through the sky. The sun will be regarded as rising at 04.40 and setting at 21.40, and the irradiation will be taken to vary like the positive part of a sinusoid between those two times (see figure 4).

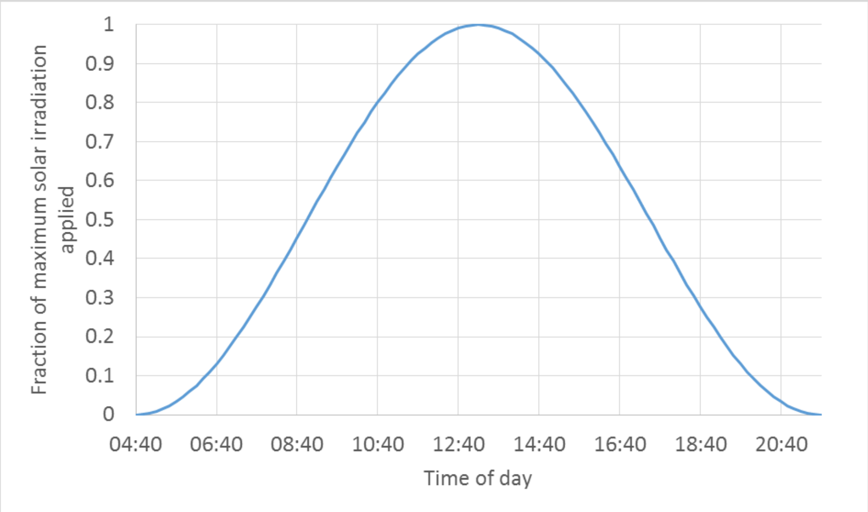

Figure 4: Irradiation variation over time. The same sinusoidal variation between minimum and maximum values was used for the external air temperature.

It is suggested that the irradiation is applied to one wall and the ceiling. Implementation of a "moving sun" model would be computationally challenging and may not represent a worst case scenario.

The Met Office website [3] suggests that the mean maximum temperature in Manchester occurs in July and is 21 °C and the mean minimum temperature in July is 12 °C. The external air temperature will be assumed to vary between those two temperatures using a function the same shape as that shown in figure 4.

It will be assumed that the peak load on the transformer and hence the peak top oil and bottom oil temperatures occur at the same time as the peaks of air temperature and irradiation. This combination will lead to a worst case scenario.

As with the previous models, the transformer is taken to be the only source of heat inside the building. The other objects inside the building will not gain or lose heat.

The wind will be considered by altering the pressure distribution on one side of the building, see section below for details. As with the previous models, the wind will be taken to increase the pressure on a face by 25 Pa.

The transformer thermal loading (top & bottom oil temperatures) will be defined by choosing the maximum temperatures reached by the most heavily loaded transformer from the sites due to undergo retrofitting. The list of these sites will be supplied by Ricardo, and the data gathered in summer 2018 will be assessed to define suitable temperatures.

The use of a transient model may mean that the method for defining how the transformer adds energy to the air needs to be altered. The measured top oil temperatures increase due to loading of the transformer and decrease due to the effects of the cooling air. Since the model needs to predict the cooling in order to look at the effectiveness of the proposed changes, it may be that an alternative approach needs to be taken. One possibility would be to estimate the internal energy of the transformer at its hottest and generate a model that cools the transformer, updates the internal energy as it loses that energy, and calculates a new transformer temperature distribution based on the new energy. This idea will be pursued in the initial stages of the project and an approach will be agreed with the project partners before the models are run.

If the specification of the transformer heat does not need to be changed, the transformer temperature distribution will be defined by identifying a time period including the highest top oil and bottom oil temperatures seen by the selected transformer, using this information to define a suitable temperature vs time curve for the two measurements, and defining a temperature distribution that interpolates linearly between top oil and bottom oil with height.

It will be assumed that the top oil and bottom oil sensor locations are the same as the locations of the equivalent sensors in the Town Bridge substation so that a height-dependent temperature distribution can be defined.

2.1.3 Model variations to be run

Each geometry will be run with the following conditions:

- A run of the building design exactly as specified under the thermal conditions specified as above with no wind and the "tight" specification for the plant placement. This situation is regarded as the base case.
- Two runs with the wind impinging on one wall leading to an increased pressure specification on that wall.
- A set of at most three models with altered louvre placement to attempt to improve air flow.
- A single model with the base case conditions and the spaced configuration.

- A single model with the spaced configuration and the conditions that gave best cooling of the tight configuration model.

This gives eight models per geometry and 16 models in total.

Four further models using non-standard build geometry will be created: two with the geometry as it currently is and two with ventilation adjusted based on the recommendations to support the retrofitting.

If time allows, more models may be added based on initial results.

“Altered louvre placement” here could mean the addition of extra louvres, addition of a ceiling louvre (GRP only), movement of existing louvres, or reorientation of louvres to encourage air to leave or enter the building.

3 ADDITIONAL APPROXIMATIONS AND ASSUMPTIONS

This section defines some additional approximations made in the model development process, and the changes made to the models as described in the previous report [1]. These changes are largely motivated by the change to a transient model. The reasons for the changes will be discussed in section 3.1, and the main changes (transformer modelling and temperature boundary conditions for all buildings, inclusion of the thermal mass of the building for brick enclosures, and consideration of initial conditions) are discussed in sections 3.2 to 3.5.

3.1 STATIC AND TRANSIENT MODELS

The models used in Phase 1 of the work were all steady state models. Steady state models are a snapshot of a system that is not changing. They are useful to understand the air flow and temperature distribution in a building where the heat load generated by the transformer and the air temperature are not changing significantly, and they are useful for validation of the basic approach used in this work. They do not provide an understanding of how the variations of heat load and air temperature might affect the cooling of the transformer.

Transient models simulate the time-dependent behaviour of the system and can look at transformer temperature in different scenarios, so they are a more effective way of comparing the effects of different ventilation mechanisms on the cooling of assets. The output of a transient model is a set of values of temperature, pressure and velocity at a set of time steps chosen by the user.

Transient models take longer to produce results, and are generally more prone to errors than steady-state models. In order to calculate the results at time steps chosen by the user, the computer calculates the values of the temperature and other variables at a series of intermediate time steps. The sizes of these intermediate steps are chosen by the software to meet its internal accuracy criteria. The values of the variables at one time step are dependent on the values of the variables at the time step immediately before, and the accuracy criteria are generally associated with the change in variable values over the time step. This dependency has two effects:

- if a system is changing rapidly, the time step chosen by the software must be small, thus making the overall computation time larger, and
- if there is a small error in a value for one time step, the error can potentially increase in all subsequent time steps.

In most cases excessive accumulated errors cause the software to crash, but these cases are difficult to identify in advance. These effects make transient models more challenging to develop and more time-consuming to solve.

Development of transient models also requires more careful consideration of the physical processes involved. For the models discussed here, there are four main changes to be considered:

- Transformer model: the previous models assumed perfect knowledge of the transformer temperature distribution. The evolution of the transformer temperature distribution is a key output of the transient models.
- Air inlets and outlets and external air temperature: the changing temperature conditions within a building may mean that an aperture is an inlet at some times and an outlet at other times. This condition is not easy to simulate efficiently.
- Thermal mass: in a steady-state scenario the effects of the thermal mass of a building can be addressed by using an altered boundary condition, as described in section 3.4.5 of the previous report. In a transient model, the thermal mass needs to be accounted for separately so that any heat stored by the building can be accounted for correctly.
- Initial conditions: a transient model requires definition of an initial set of values for the quantities being calculated, but the initial state of the temperature and velocity inside the building is unknown (and unknowable). Whilst point measurements are available for specific buildings, these are not sufficiently extensive to be able to deduce the temperature of the air everywhere in the building.

These considerations will be discussed in sections 3.2 to 3.5.

3.2 TRANSFORMER MODEL

For the purposes of this work, the transformer is essentially just a heat source. The transformer generates losses when it transforms the voltage of the electricity, the losses are dissipated as heat that gradually spreads throughout the transformer, and the resulting increase in transformer surface temperature leads to convective losses to the air in the building. The transient model needs to ensure that the amount of energy added to the system is representative of the losses from the transformation, and that the time delay between the transformation generating energy and the surface temperature of the transformer reaching a peak is consistent with measured values and observations.

Discussions with Ricardo experts suggested that they expected about 20 kW losses for a fully loaded 1000 kVA transformer, and that they expected a delay of about 1.5 hours between peak losses and peak transformer surface temperature.

The simplest way to simulate the energy coming into the building from the transformer and the delay between the peak in generation of the energy and the peak in surface temperature is to model the transformer as a solid material with a heat flux applied internally. Adjustment of the solid material properties ensures that the correct delay occurs, and adjustment of the heat flux ensures that the correct total energy is delivered. This approach adds to the computational complexity of the model and requires care in setting up the interchange of heat between the solid and the air, but it is a reasonable physical approximation to reality.

A simple one-dimensional model of heat transfer was used to fit model results to measured surface temperature values to obtain the unknown material properties. In order to reflect the thermal stratification that occurs within the transformer, the heat flux was treated as varying linearly with height, and temperatures measured at a high and low point on the transformer surface were used for the fitting. The temperature values used came from the Town Bridge transformer, which is expected to be not fully loaded. The best fit results found are shown in figure 5, and show a good level of agreement given the simplicity of the model used.

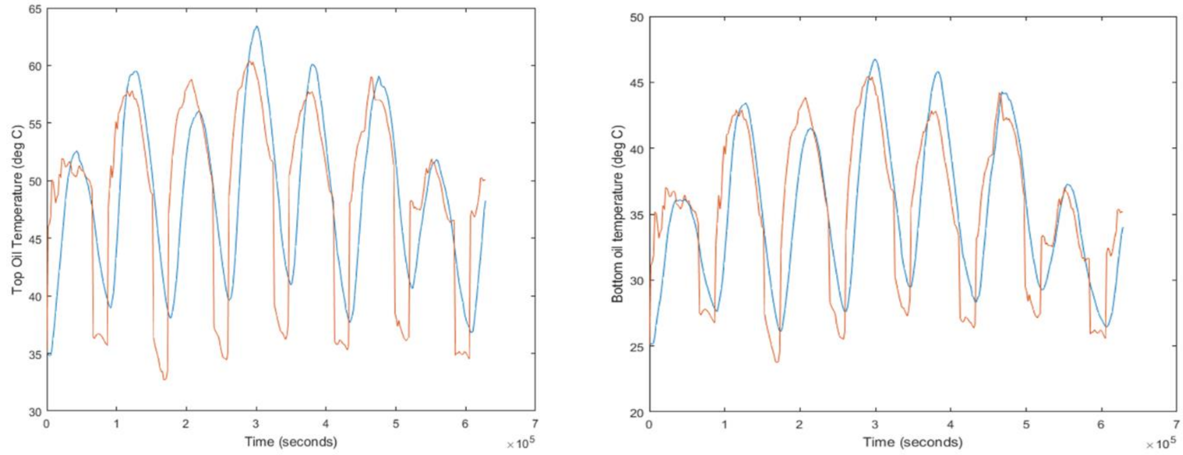

Figure 5: Best fit results, comparing calculated and measured values of transformer surface temperature. The blue lines are the measured temperatures and the orange lines are the model results. The left hand plot is for a position high on the transformer, and the right hand plot is for a position low on the transformer.

The best fit values found were a thermal mass (specific heat capacity × density) of 157 kJ m^{-3} and a thermal conductivity of 0.2 W m^{-1} K^{-1}. These values are equivalent to a delay of 1 hour 11 minutes, which is consistent with expert opinion. The heat flux was found to be 2.88 kW m^{-2} at the top of the transformer, and 1.44 kW m^{-2} at the bottom. Taking the area of application into account, these values are equivalent to a heat input of 5.6 kW. This value is consistent with expert opinion under the hypothesis that the transformer is not fully loaded. Investigation of a more heavily loaded transformer could be undertaken by increasing these values. It is likely that the effective properties estimated are a function of the design of the transformer.

The agreement between the model and measurements was agreed to be sufficient justification for using the approach described and the values identified.

3.3 AIR INLETS, OUTLETS, AND TEMPERATURES

The air flow into and out of the building is dependent on the pressure and temperature of the air inside and outside of the building, and in reality air can flow in or out of any given aperture depending on the local temperature and air pressure. Ideally the model would allow this change in flow, and would ensure that air entering the building was at the external air temperature, and air leaving the building was at the internal air temperature. If a sufficiently large computer were available, the perfect model would include a volume of air surrounding the building in order to allow the air leaving the building to mix with the (generally colder) external air.

In practice, this approach is beyond the capabilities of the computing resources available for this work. The software allows for flow out of areas defined as inlets and flow into areas defined as outlets, so capturing changes in flow direction is not a problem, but the associated change in air temperature cannot be handled. As a result, if flow in through an outlet is permitted and the temperature of the incoming air is not defined as air temperature then the results may be misleading.

It has therefore been decided to define the air temperature of all zones that are inlets or outlets as being the ambient temperature (a sinusoidally varying function of time, as stated in the specification). The effect of this assumption is that the temperature of air leaving the building is artificially low. It is expected that the effect will be localised and will not affect the results in most of the building.

3.4 THERMAL MASS

GRP buildings are thin structures and therefore lose and gain heat quickly. Brick structures are thicker and denser and so store and release heat over a longer timescale. This storage, which has been extensively observed in real substations, needs to be accounted for in the models of brick buildings.

An attempt was made to use a "thermally thick" boundary condition to approximate the thermal mass of the building, but initial test results suggested this was not accurate enough to be reliable, so a full 3D model of the heat flow within the brick structure has been developed.

The model of heat flow within the structure requires a thickness and a set of material properties (density, specific heat capacity and thermal conductivity) to be defined for the wall and roof. The wall thickness is specified in documents supplied by ENWL as 280 mm. The roof thickness has been chosen such that the volume of the roof is the same in the model as it is in the specification document, i.e. the effective thickness is taken as half of the peak roof height. This value is 525 mm. This approach smears out the overall effects of the roof but ensures that the correct amount of energy is stored in the structure.

The CIBSE guide to environmental design [2] gives values for U-values and heat capacity per unit area for specific wall and roof structures. The structures listed include:

- 220 mm solid brick wall, 50 mm air space/battens, 12.5 mm plasterboard (U-value 1.41 W m^{-2} K^{-1}, heat capacity 37 kJ m^{-2} K^{-1}),
- Uninsulated pitched roof, 12.5 mm plasterboard, tiling (U-value 2.3 W m^{-2} K^{-1}, heat capacity 8 kJ m^{-2} K^{-1}).

The structural document supplied by ENWL shows that the description of the roof agrees well with the description above, and that the wall descriptions differ only in the lack of plasterboard in the ENWL document. The plasterboard is thin in comparison with the bricks and is unlikely to contribute significantly to the thermal mass or the U-value.

The values listed above have therefore been used to calculate equivalent properties for the required boundary condition. The thermal conductivity is calculated by multiplying the U-value by the nominal thickness of the layer, the density is set at 1600 kg m^{-3} (consistent with the previous report [1]), and the specific heat capacity is equal to the heat capacity divided by the product of the density and the nominal thickness.

The consideration of thermal mass means that re-radiation from the building surface has to be taken into account to ensure that the building temperatures are accurate. The GRP models did not take this re-radiation into account in all models, but a single version of the basic model was run to assess the extent of the differences. The results of this test are presented in section 5.

3.5 INITIAL CONDITIONS

As stated above, transient models require definition of an initial set of values of the unknown quantities. Because the initial state of the temperature and velocity inside the building is unknown (and unknowable), a steady state model using the air temperature and heat flux at zero time was used to estimate the initial state. This approach is a standard technique and is more likely to be accurate than any estimation by hand.

The effects of the assumption have been assessed by running four of the models for a longer time period: for each building, the base case and the best performing altered building have been run over a period simulating five identical days. The results of these longer runs are discussed below.

4 ALTERED GEOMETRIES

This section discusses the ways in which the internal geometries of the buildings were altered to try and improve the cooling.

4.1 GRP BUILDINGS

Figure 6 shows the basic GRP building from two angles.

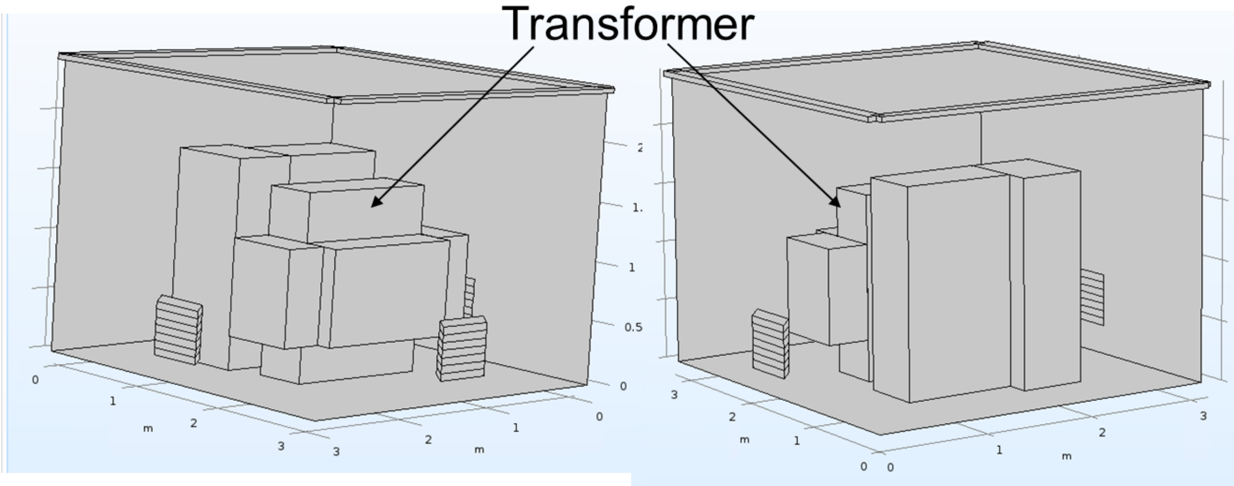

Figure 6: GRP building layout from two angles.

The GRP buildings were altered by adding extra louvres and by attempting to steer the air out of the building. The simplest change was to add a single flow director to each louvre. This was a single plate of width 14 cm placed at an angle of 45 degrees at the bottom of the louvre. This alteration is pictured in figure 7. The intention was that the plate would steer the air outside.

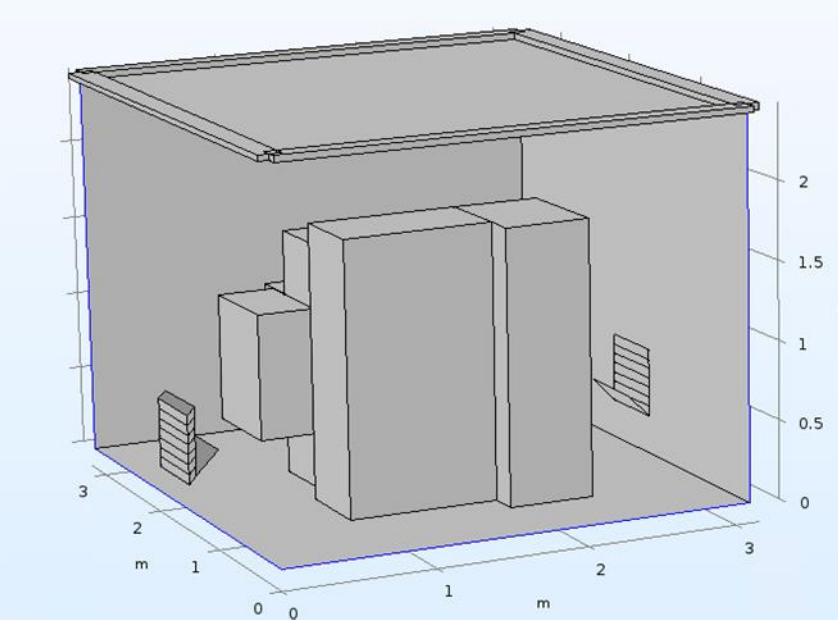

Figure 7: Model with added plates.

The second alteration added a second set of louvres to the building. The louvre designs were identical to the original louvres and were placed vertically above the original louvres, separated by a distance of

1.12 m. Two separate models with these extra louvres were run: one with plates on the upper louvres, and one without. An illustration of the alteration with extra louvres and plates is shown in figure 8.

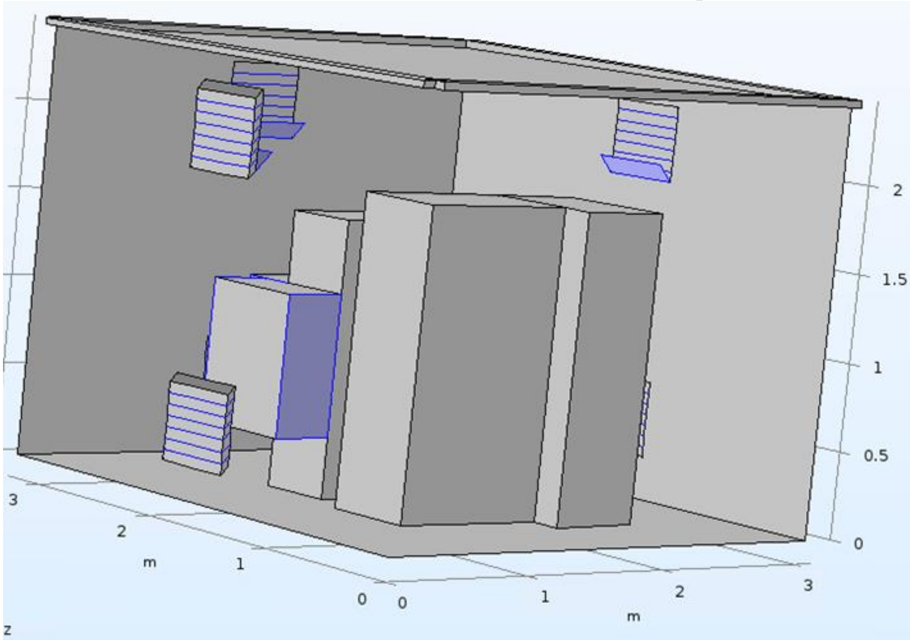

Figure 8: Model with extra louvres and plates.

The third alteration constructed a large chimney (1.5 m by 1.5 m by 0.75 m) in the centre of the roof and added 1.4 m wide louvres to it. This alteration is shown in figure 9.

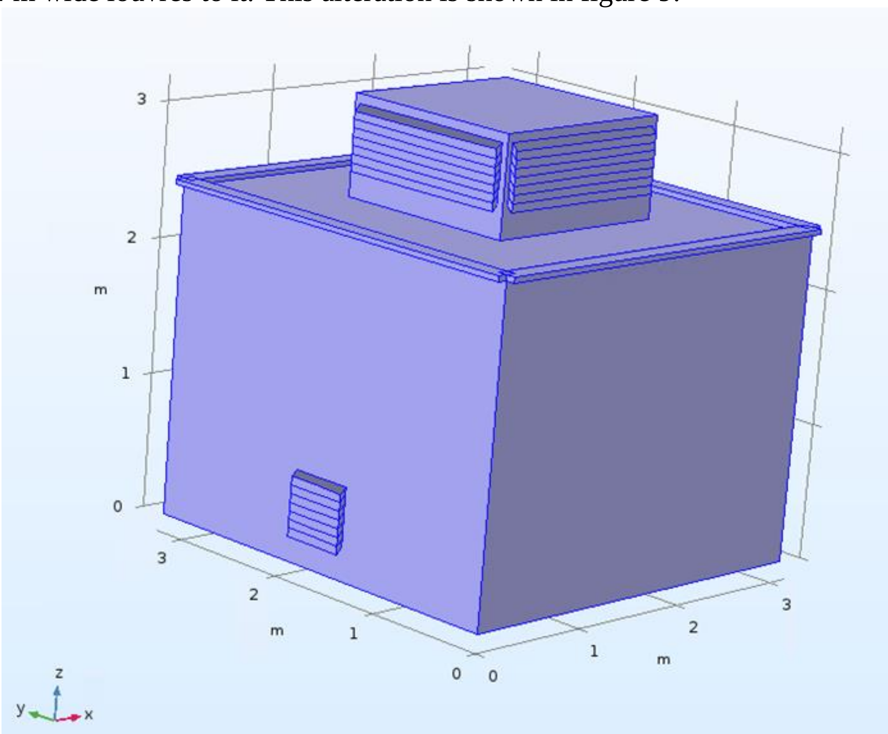

Figure 9: Model with a chimney.

The fourth alteration added an extra set of louvres the same size as the existing louvres, but placed all louvres low down in the building, near to the corners. This arrangement is shown in figure 10.

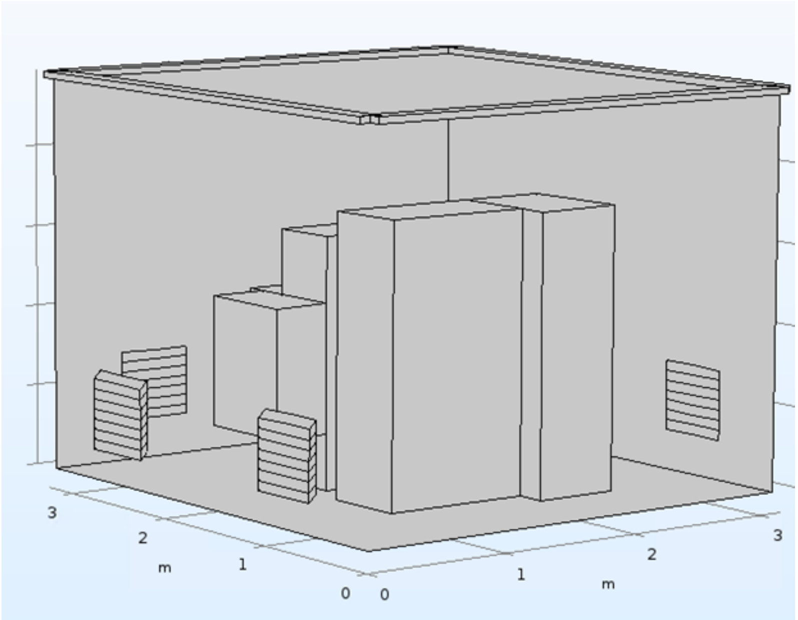

Figure 10: Model with extra louvres low down.

After inspection of the real buildings, it became clear that placing louvres at the centre of a wall was not feasible due to the presence of a reinforcing post in the centre of the wall. Three designs with offset louvres were therefore created to examine the effect of non-central louvre placement. Figure 11 shows an arrangement with the louvres on the side walls shifted towards the transformer as a pair; figure 12 shows a design with the high louvres shifted towards the transformer and the low louvres shifted towards the door, and figure 13 shows a three-louvre arrangement with two low louvres close to the transformer on the side walls and one high louvre on the back wall. In all these figures, the RMU and LV cabinets have been removed for clarity.

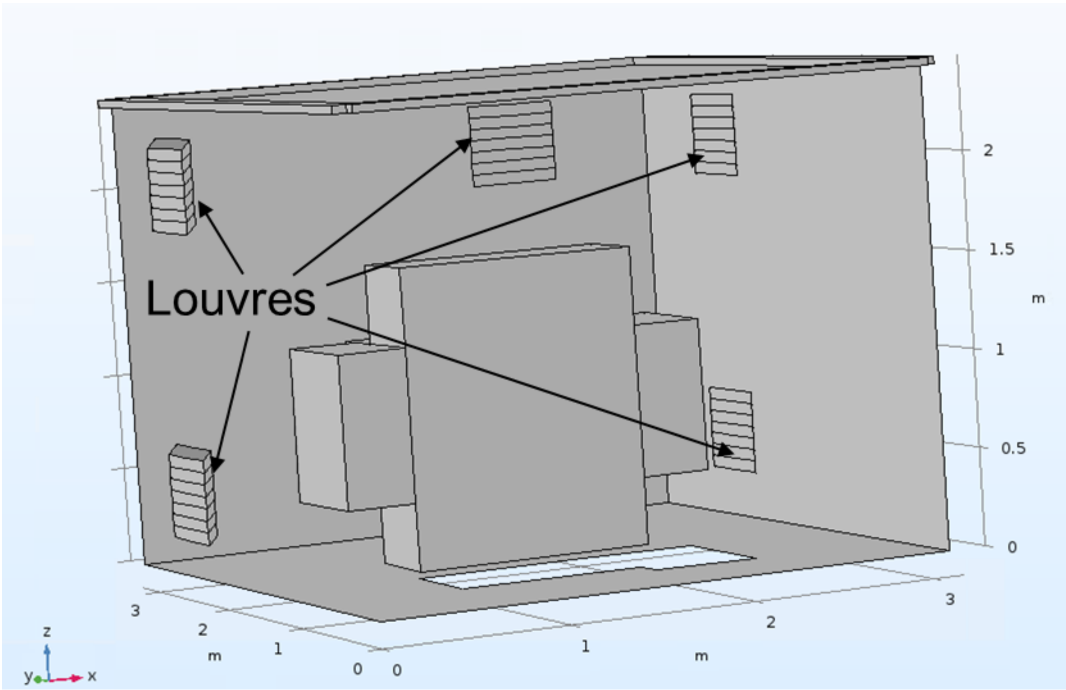

Figure 11: Model with louvres shifted closer to the transformer. A sixth louvre is low down below the high louvre on the back wall and is hidden behind the transformer.

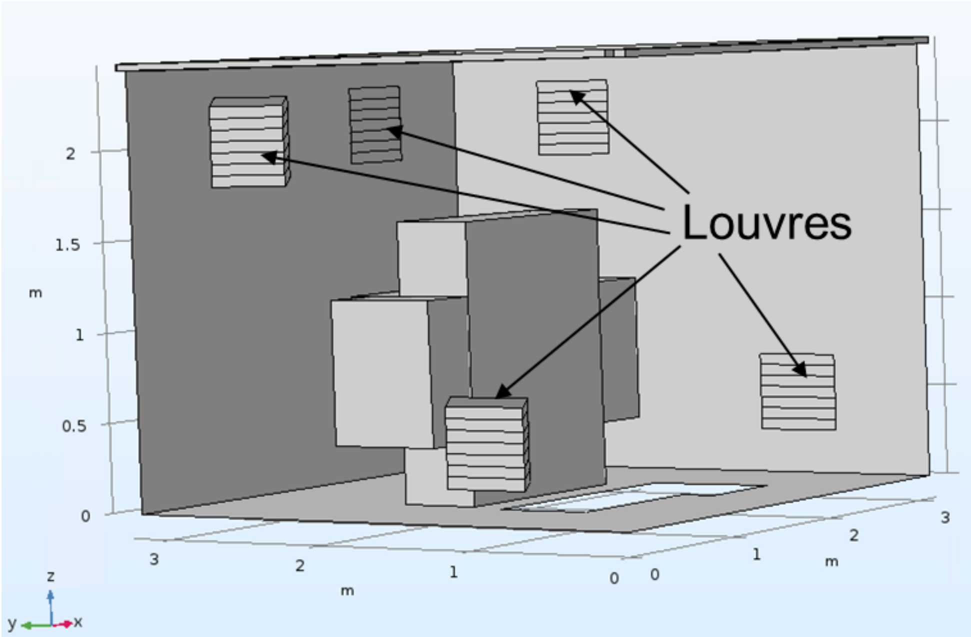

Figure 12: Model with high louvres shifted closer to the transformer and low louvres shifted closer to the door. A sixth louvre is low down below the high louvre on the back wall and is hidden behind the transformer.

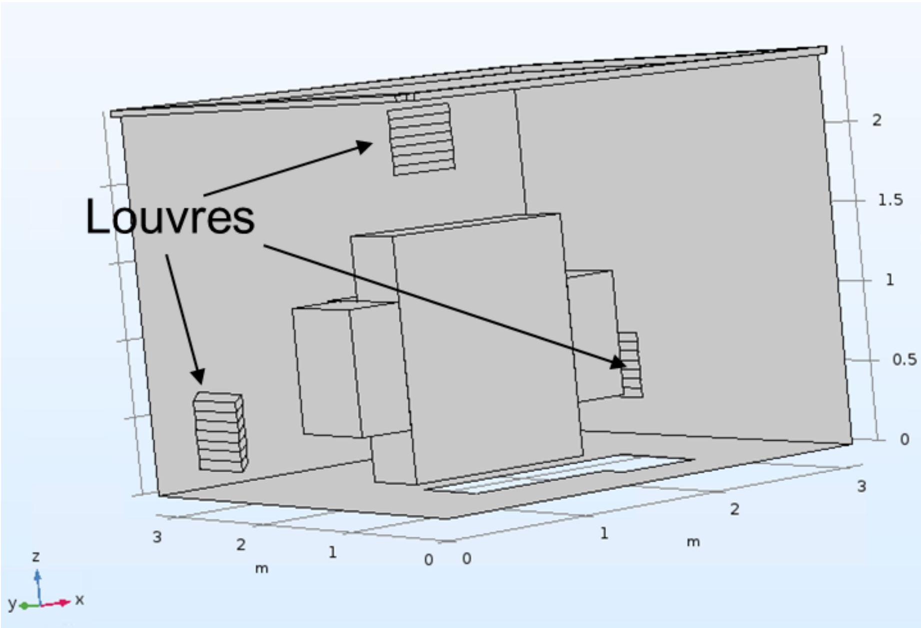

Figure 13: Model with three louvres at different heights: two low on the side walls near the transformer and one high on the back wall.

4.2 BRICK BUILDINGS

Figure 14 shows the basic brick building from two angles. The use of solid volumes to define the roof and walls means that the inner chamber containing the transformer is a distinct region within the model and within the following figures. The brick building basic design has a single pair of louvres on the side wall. Only one run has been performed with raised pressure on the louvres because the louvres would both be under pressure due to wind-loading at the same time, and wind loading on a wall with no louvres would have no effect.

The first alteration made was to move the louvres to the back wall so that all of the cold air impinges directly onto the transformer. Subsequent alterations added an identical pair of louvres onto the opposing side wall, as shown in figure 15, and a total of three pairs of louvres, one pair per wall, as shown in figure 16. Finally two chimney designs were tested. The first had a single pair of louvres in the walls and a single chimney louvre, and the second had two pairs of louvres in the walls and one pair of louvres in the chimney (as shown in figure 17). It was assumed that the chimneys would be GRP or another material of low thermal mass, so their surfaces were included in the solar radiation but they were not given a thermal mass.

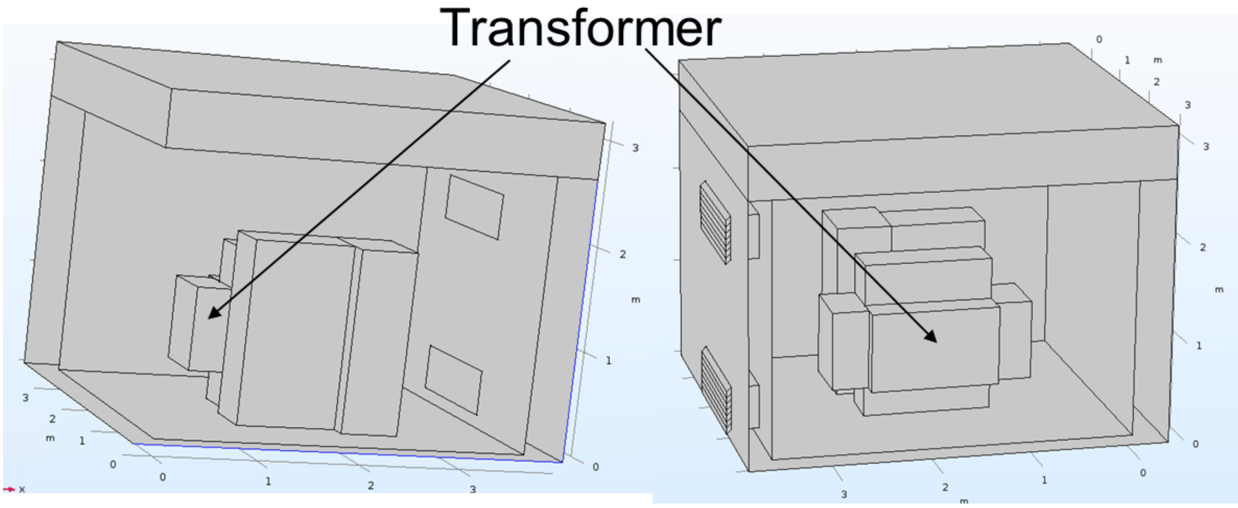

Figure 14: Base case for the brick buildings from two angles.

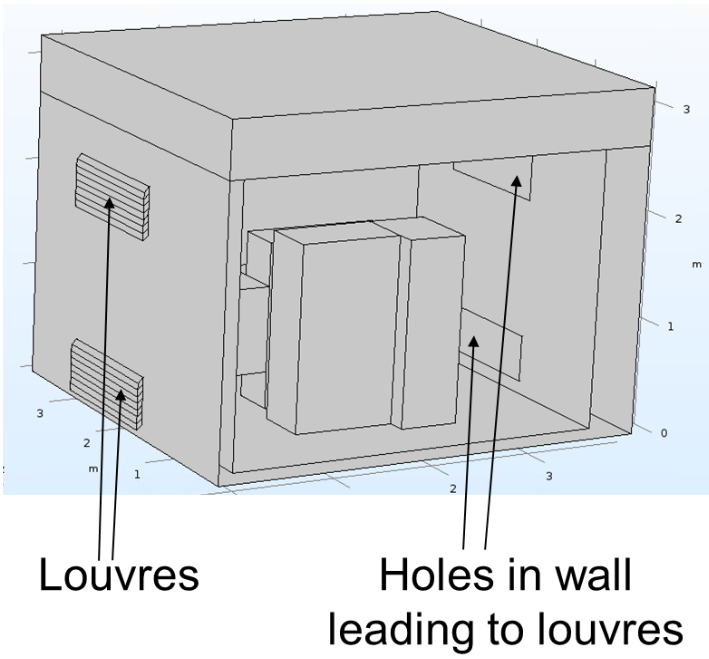

Figure 15: Model with two pairs of louvres.

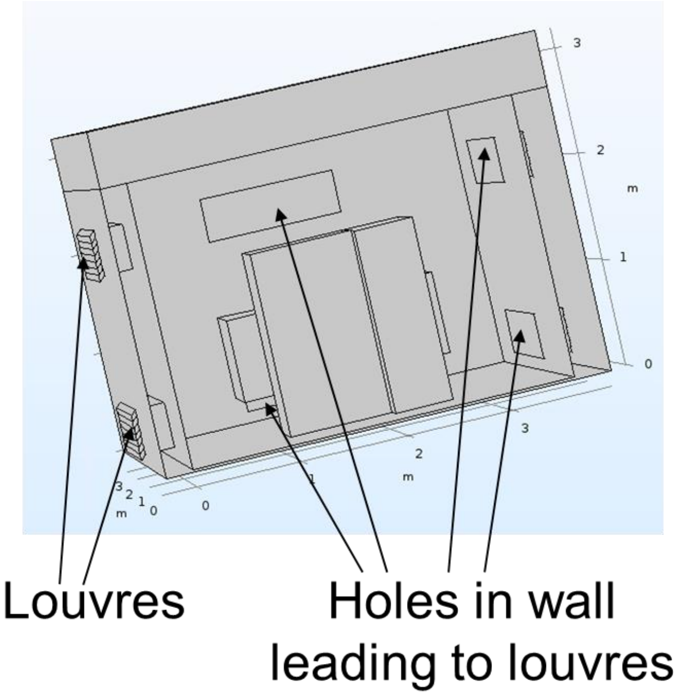

Figure 16: Model with three pairs of louvres.

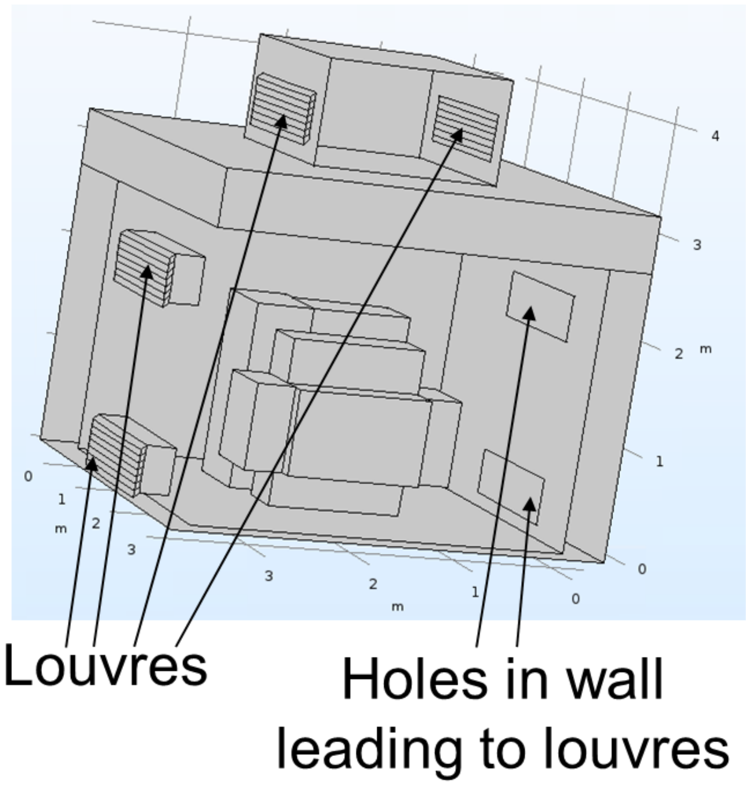

Figure 17: Model with two pairs of louvres in the walls and a chimney with two louvres.

5 RESULTS

This section reports the results of the various models.

The sections below refer to “change in energy removed”. This quantity is intended to represent improvements in cooling, and is calculated as follows:

- The rate of energy transfer from the transformer to the air at each output time step is calculated directly from the source terms representing convection from the main body of the transformer and from the fins. This calculation results in a total power at each time step.
- The total power is assumed to be constant over the output time period and is therefore multiplied by 1800 s (the duration of the output time steps) to give an energy transferred over that period.
- The energies over each time step are summed to give a cumulative value of energy transferred over elapsed time.
- For each geometrically altered case, the base case energy transferred is subtracted from the calculated transferred energy for that case, to highlight the change in energy transferred that the alteration has produced.

For comparison, figure 18 shows the cumulative energy removed over time for the base cases for GRP and brick buildings. The two curves are quite similar, and the final amount of energy removed is just over 30 MJ in both cases.

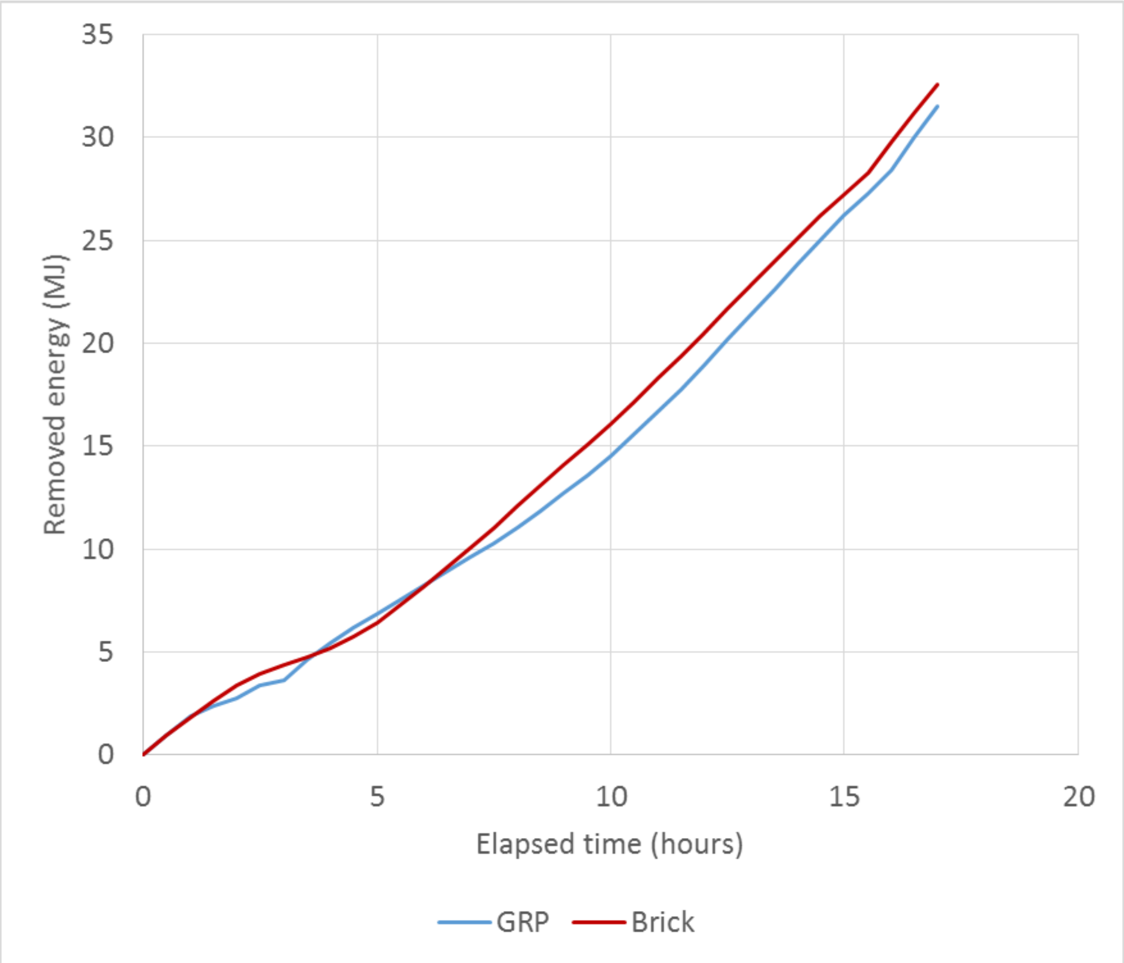

Figure 18: Cumulative energy removed for the base cases.

5.1 GRP BUILDINGS

Figure 19 shows the change in energy removed for all of the initial set of models of altered buildings. The two runs with the pressure applied to a given louvre (simulating the effects of wind) show the most significant reduction in stored energy, suggesting that the technologies for driven cooling under investigation may be more effective than ventilation alterations alone. The changes in ventilation involving extra louvres, including the chimney case, have improved energy removal by between 0.5 and 1 MJ.

Figure 20 shows the change in energy for the various offset louvre arrangements shown in figures 11 to 13 and the initial extra louvres run. The plot suggests that the cooling performance in the early stages of the day makes a big difference to the overall performance. It should be noted that the predictions at this stage are most dependent on the initial conditions, so the predicted behaviour may be an over-estimate (see section 5.3 for further discussion). The three-louvre arrangement shows greater cooling due to its performance in the early stages of the model. This arrangement has the further advantage that it is cheaper to fit.

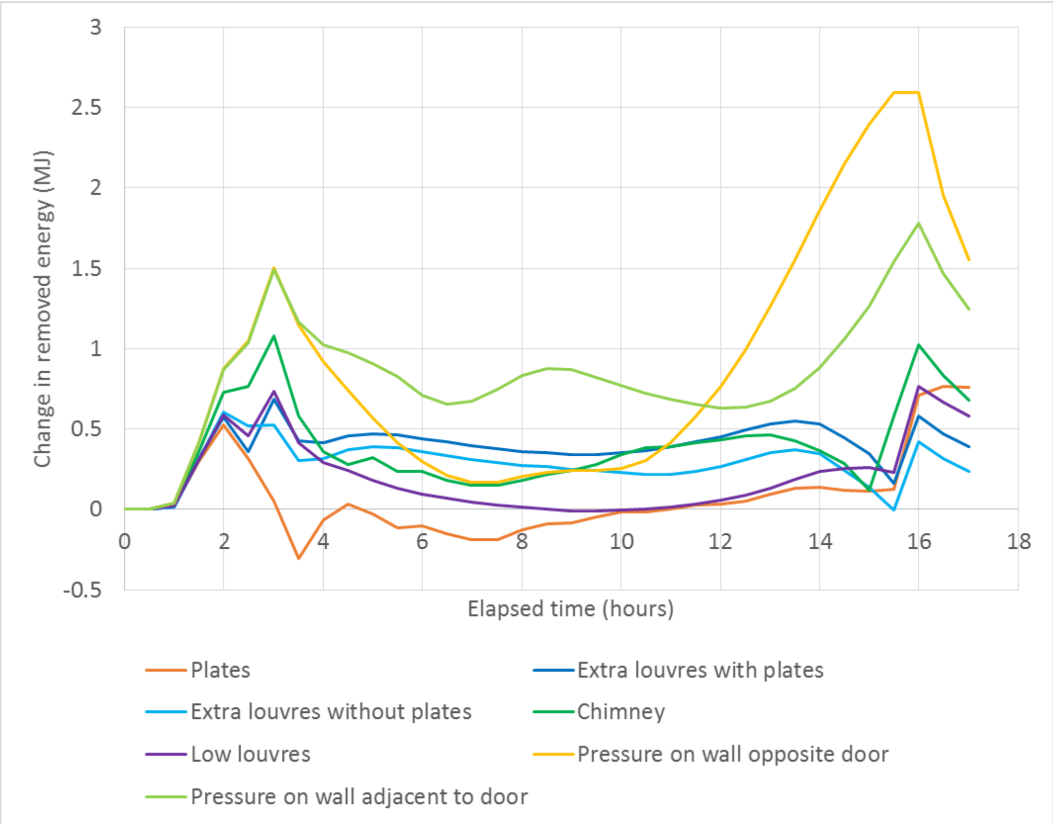

Figure 19: Comparison of change in energy removed for the various models.

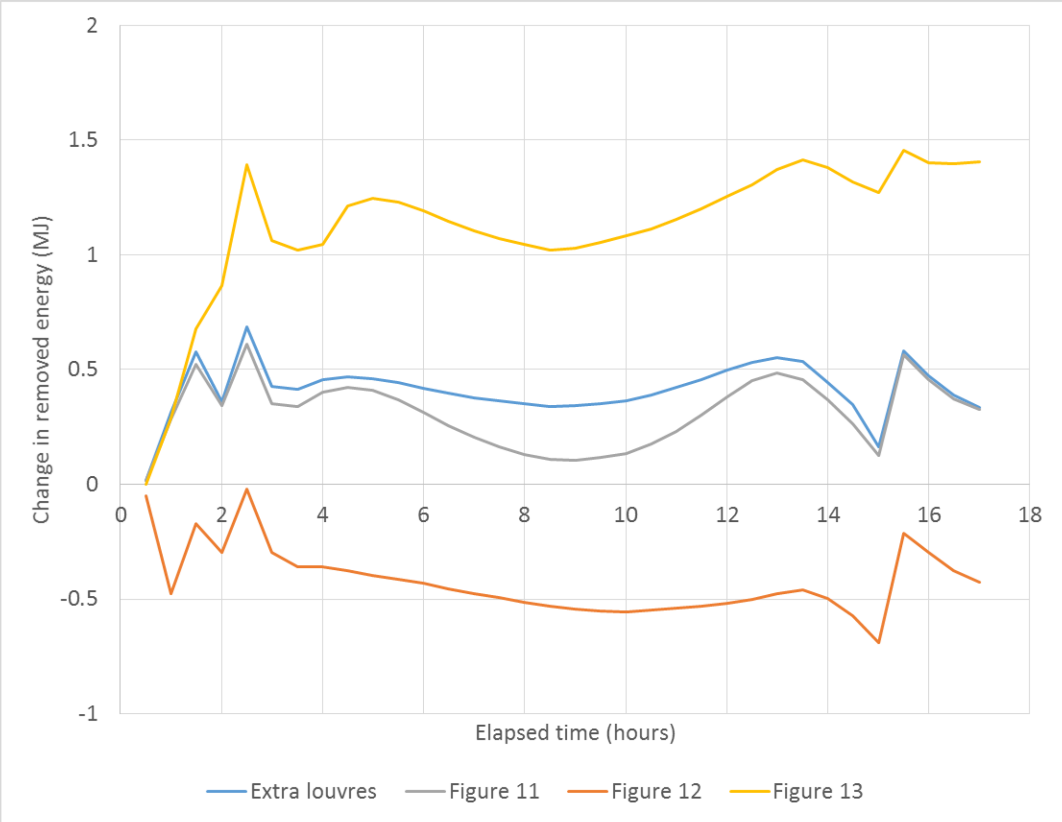

Figure 20: Comparison of change in energy removed for the models with offset vents arrangements.

A plot of the air velocity in the vertical direction at the ground-level inlets for some of the models is shown in figure 21. A positive velocity means that air is going in, and a negative one means that air is going out. All models show that the velocity undergoes a change of direction after about two hours. This figure also shows that the extra louvres and the chimney increase the flow rate of air through the building, as their inlet velocities are higher. The change of direction occurs because the flow goes from being almost static to being driven by the thermal gradients generated within the building. It should be noted that a more constantly heavily loaded transformer would therefore be expected to show behaviour typical of the thermal gradient stages and hence may not show this change in velocity.

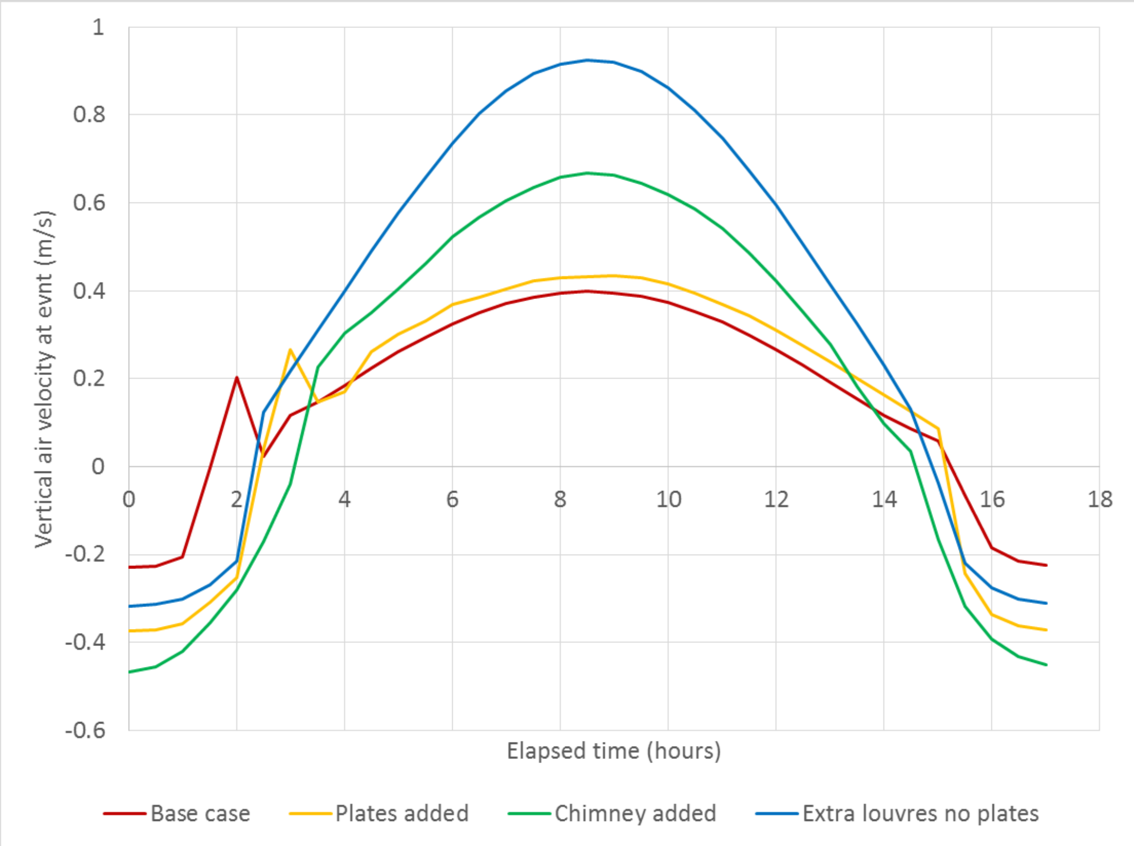

Figure 21: Air velocity in the vertical direction at the low down louvres

Figures 22 and 23 show typical air temperature and velocity plots for the base case model (note that the arrow sizes are not comparable between these plots, so the flow at time zero is not faster than that after nine hours). Initially the flow is largely recirculation, but after 9 hours the flow into and out of the louvres is more significant. These plots also show the effect of the solar heating: the air temperature at the roof is about 60 °C, well above the temperature of the air around the transformer. For comparison, figure 24 shows the air temperature and velocity in the same building without the radiative heating. The air temperature is significantly lower (if figure 24 is plotted using the scale of figure 23, everything is dark blue) and significantly more uniform.

Figure 25 shows a direct comparison between the energy removed for the cases with and without solar radiation. The case without solar radiation is able to remove more energy because the air temperature inside the building is lower, suggesting that measures to reduce the effects of solar radiation would improve cooling on sunny days.

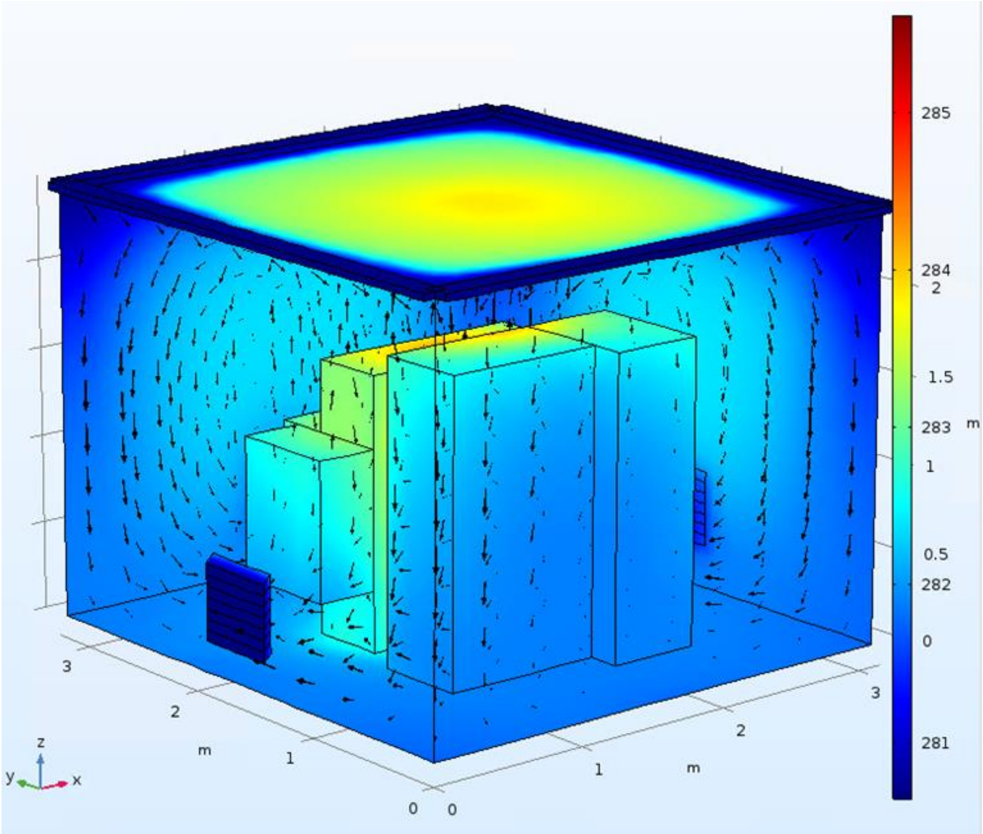

Figure 22: Air temperature (in K) and velocity for the base case at zero elapsed time.

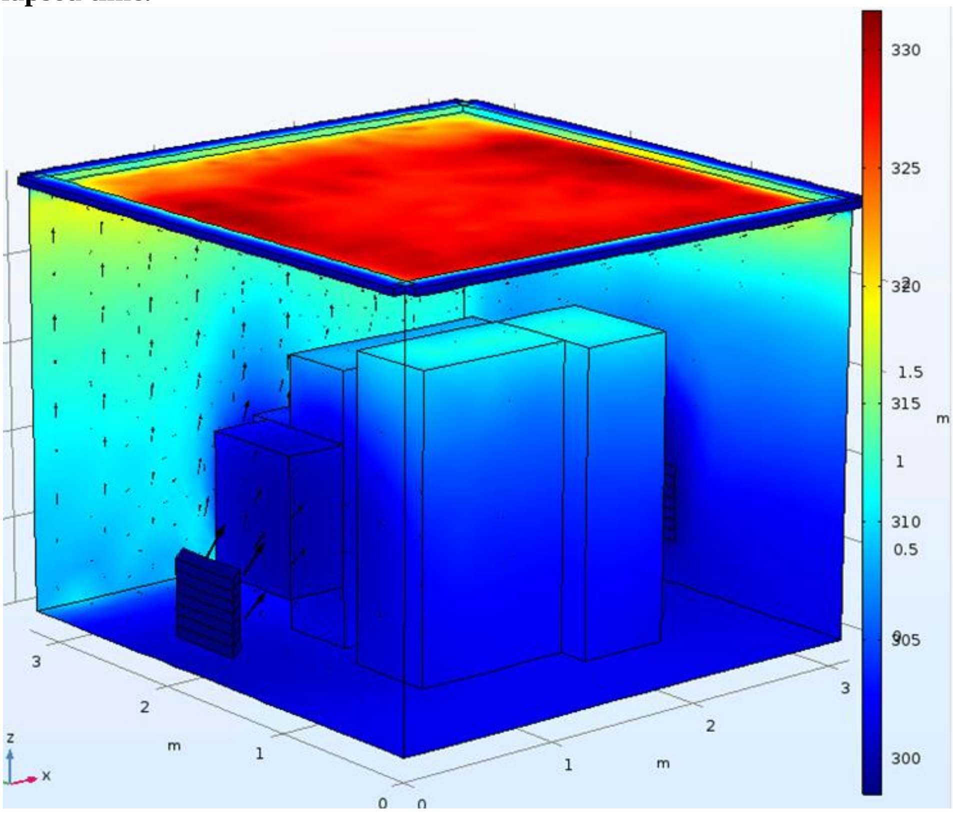

Figure 23: Air temperature (in K) and velocity for the base case at nine hours elapsed time.

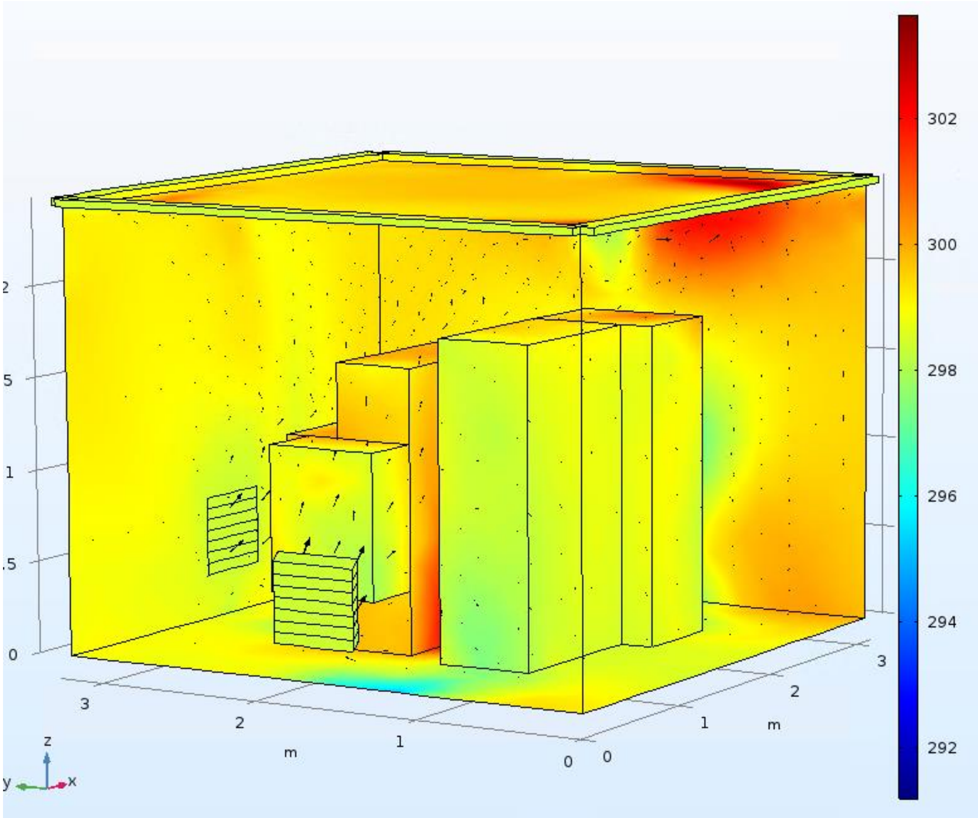

Figure 24: Air temperature (in K) and velocity for the base case at nine hours elapsed time without solar heating.

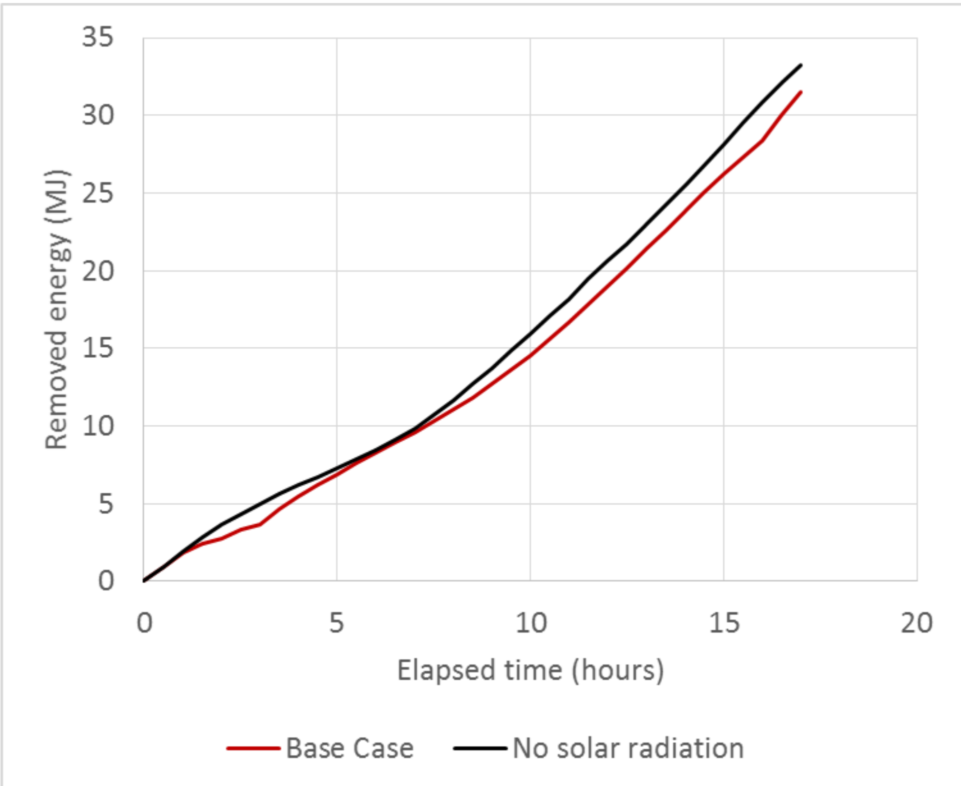

Figure 25: Energy stored in the base case with and without solar radiation.

Figure 26 shows the air temperature distribution for the case with extra louvres. The maximum air temperature is lower, and the additional air flow has reduced the temperature of the air at the ceiling.

Figures 27 to 30 show the transformer surface temperature for the base case (figure 27), the model with extra louvres (figure 28), the model with a chimney (figure 29), and the model with three louvres at different heights (figure 30) after nine hours of elapsed time. All three figures use the same colour scale (300 to 350 K). Superficially the three plots look very similar. The main difference is that the model with extra louvres has reduced the temperature on the top surface of the main body of the transformer, and the shifting of the louvres in figure 30 means that the front face of the transformer is no longer hit by cold air and so has a localised hot spot on the front of it.

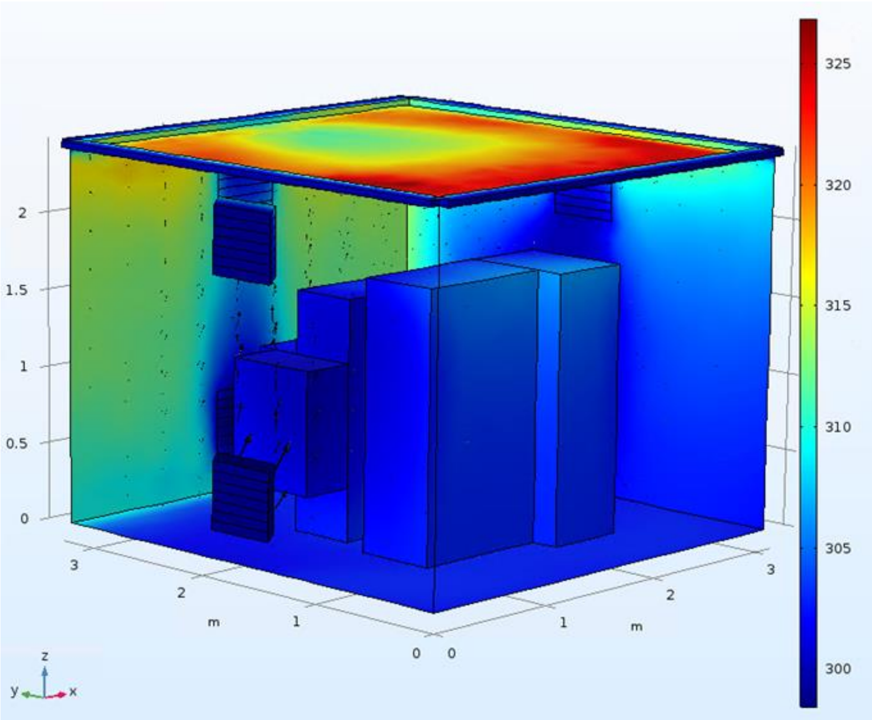

Figure 26: Air temperature (in K) for the case with extra louvres after nine hours of elapsed time.

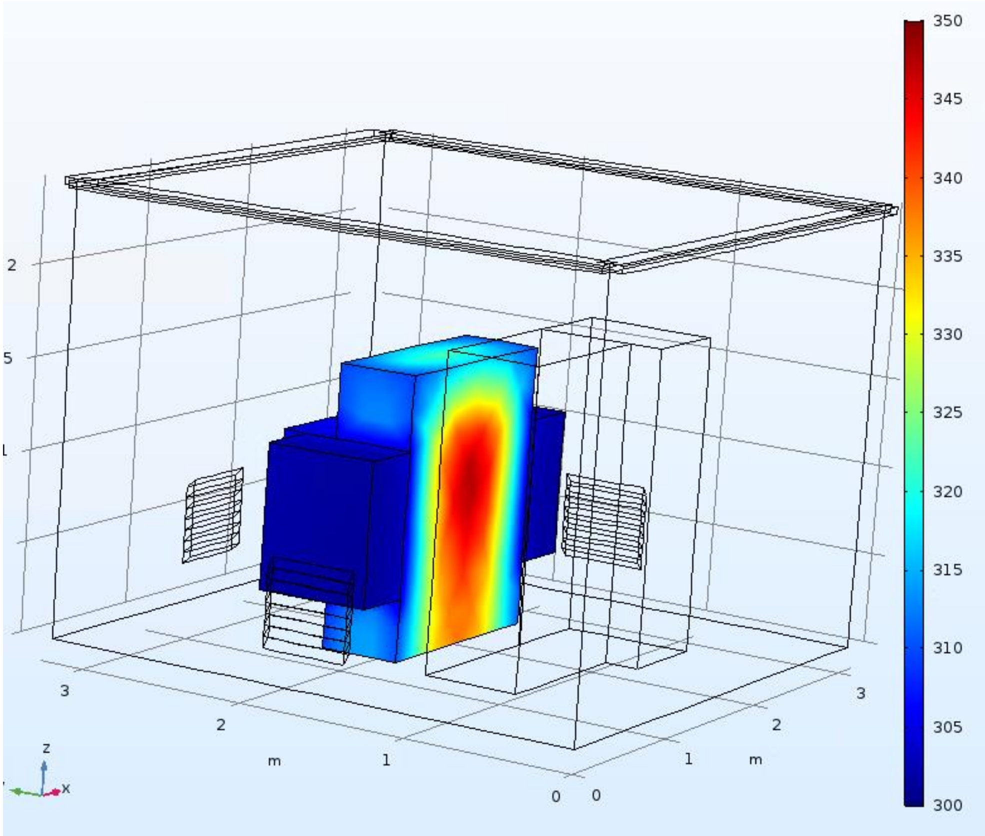

Figure 27: Transformer surface temperature (in K) for the base case after nine hours of elapsed time.

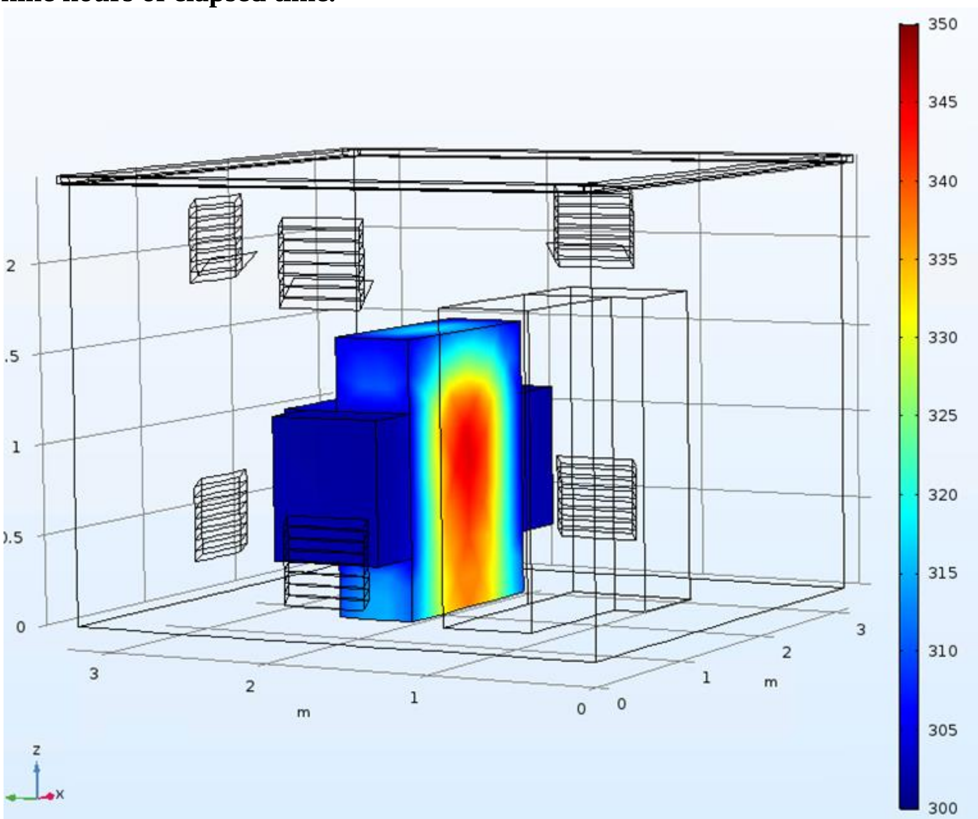

Figure 28: Air temperature (in K) for the case with extra louvres after nine hours of elapsed time.

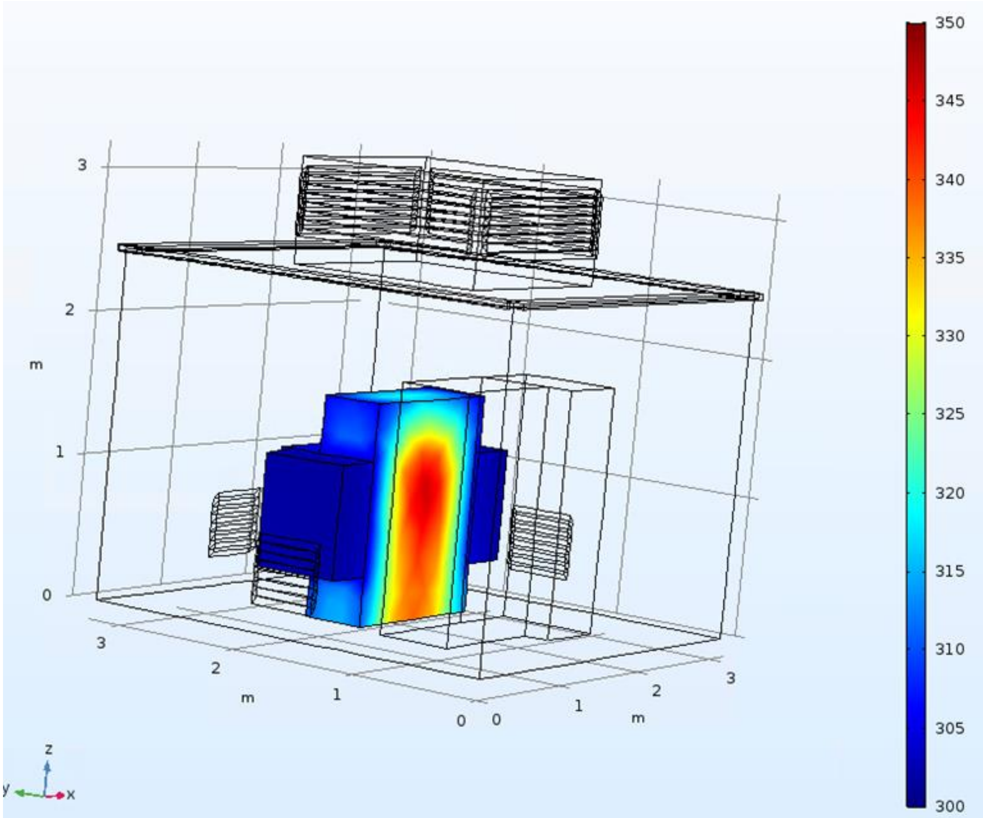

Figure 29: Air temperature (in K) for the case with a chimney after nine hours of elapsed time.

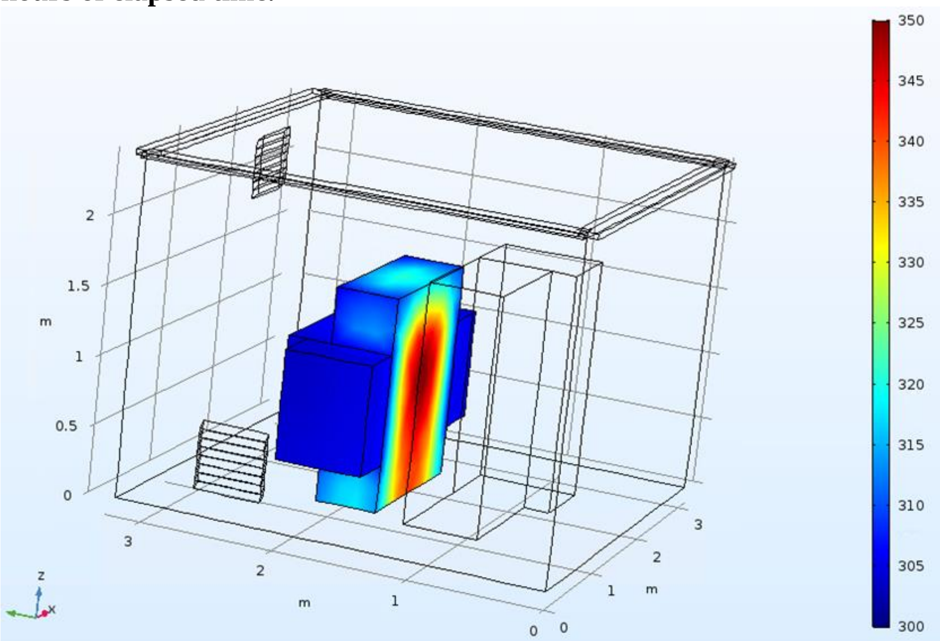

Figure 30: Air temperature (in K) for the case with three louvres after nine hours of elapsed time.

Figures 32 to 34 show the variation of transformer surface temperature over time for the base case, the model with extra louvres, the model with a chimney, and the model with three louvres at different heights. These temperatures were extracted at the points illustrated in figure 31. These plots show that the cooling measures have reduced the surface temperature of the transformer in all locations, with the reduction of the main body temperature being the most significant

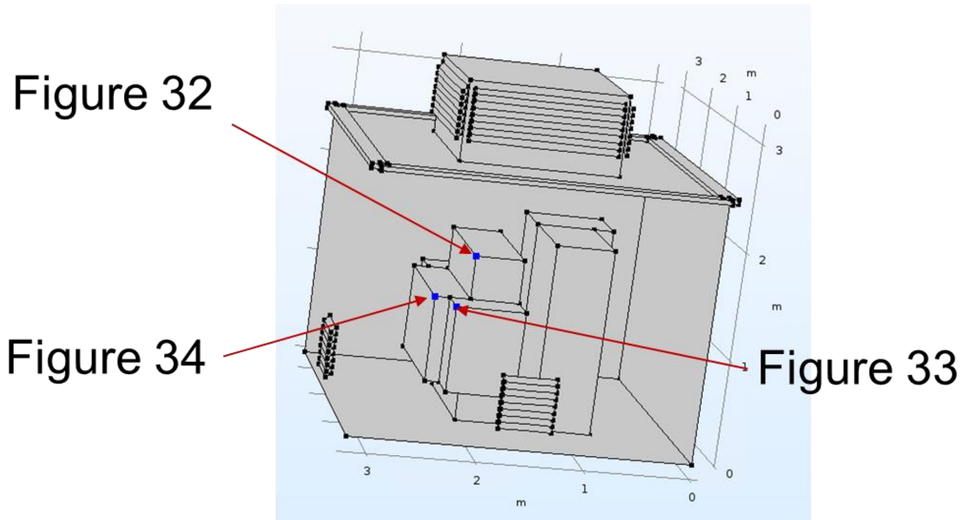

Figure 31: Locations of points for which temperatures are plotted in figures 32 to 34.

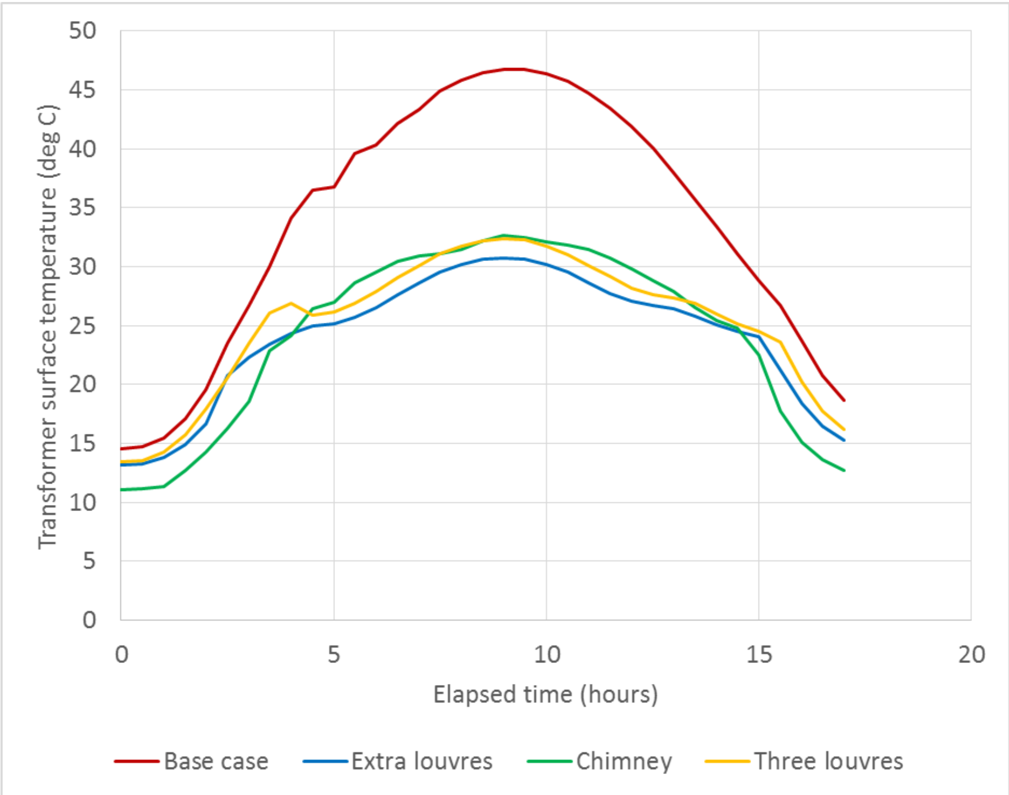

Figure 32: Transformer surface temperature at the top of the main body.

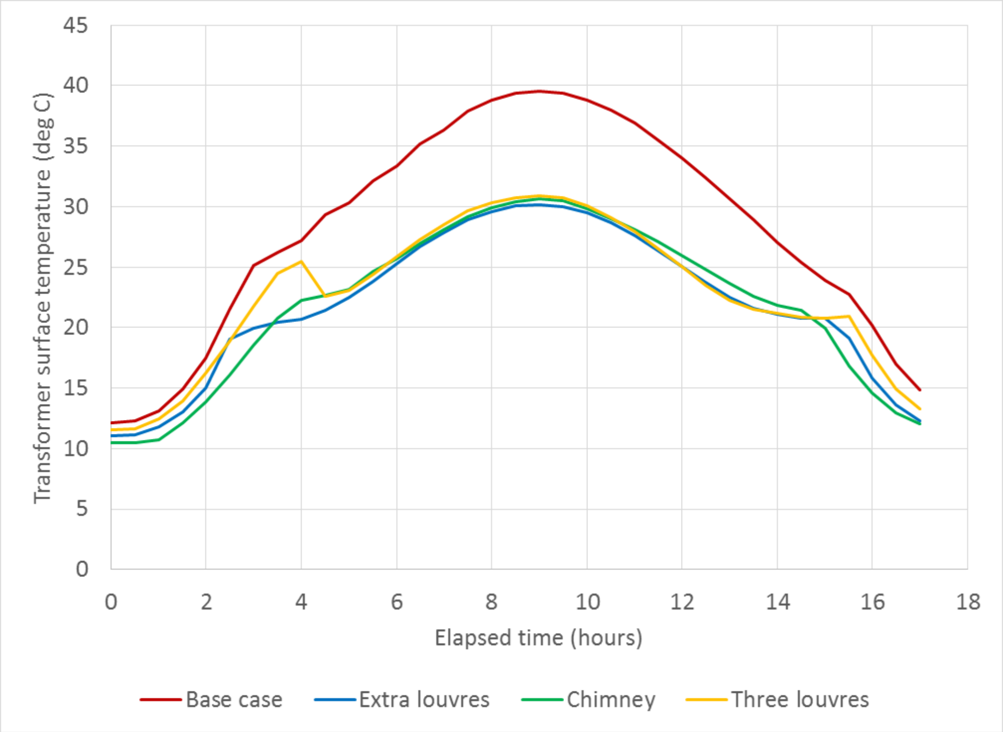

Figure 33: Transformer surface temperature at the top of the small cooling fin volume.

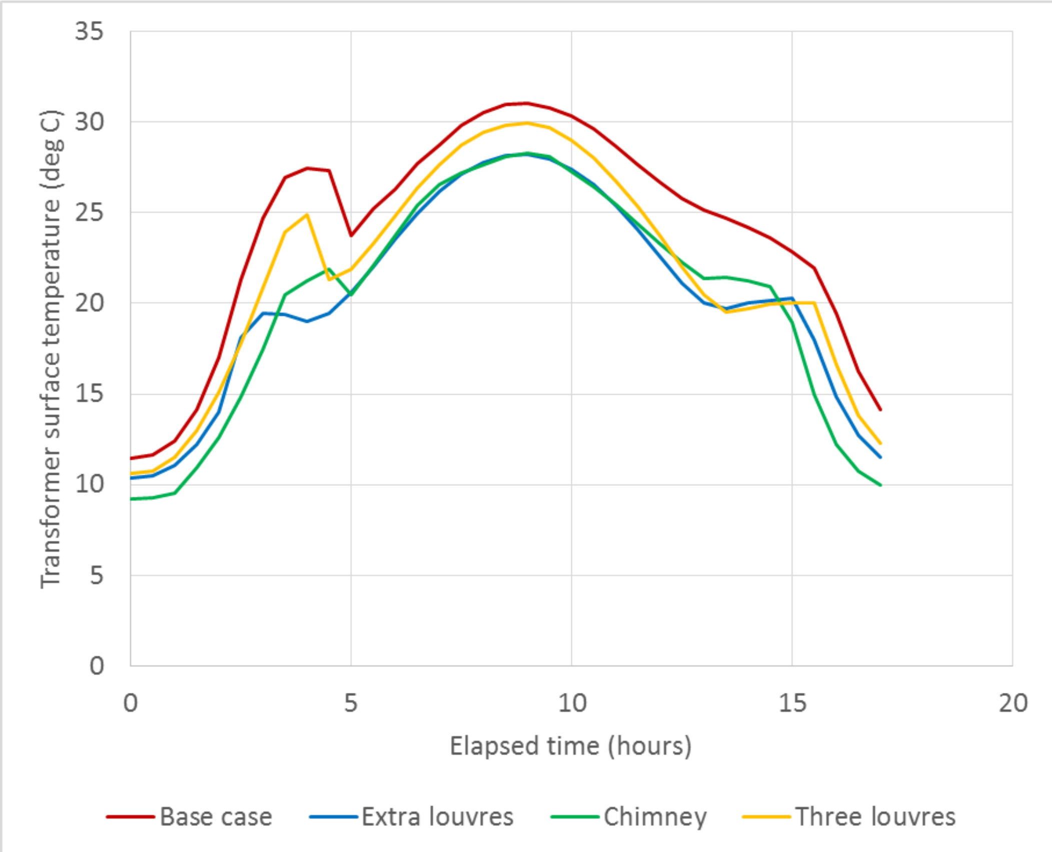

Figure 34: Transformer surface temperature at the top of the large cooling fin volume.

5.1.1 Test of re-radiation

As mentioned in section 3, the GRP models did not include thermal mass directly and neglected re-radiation from the building surface. In order to test the effects of the second of these assumptions, the base case model was run with re-radiation. A comparison of the air temperature and flow direction after 9 hours, when the differences in temperatures are likely to be at their largest, is shown in figure 35. Note that the colour contours are not to the same scale. The flow patterns are very similar, the temperature contours show the same relative distribution, and the maximum air temperature in the re-radiated case is about 5 K lower (325 K vs 330 K). These similarities are enough to demonstrate that the conclusions drawn about air flow improvement would apply to the model with re-radiation as well.

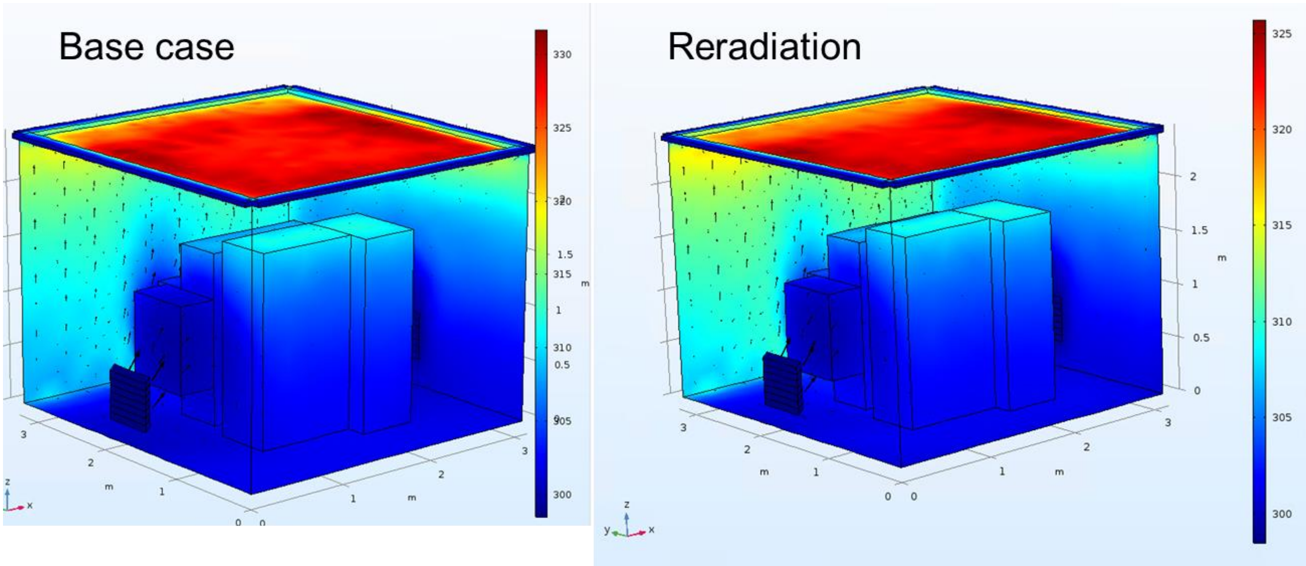

Figure 35: Direct comparison of the base case model and the same model with re-radiation from the surface.

5.2 BRICK BUILDINGS

Figure 36 shows the change in removed energy for the various altered buildings. All of the changes are negative, suggesting that the proposed changes have made things worse. It is suspected that the lack of improvement is largely due to the thermal mass of the building: the increase in cold air entering the building through the extra louvres cools the building more than it cools the transformer because in many cases the model predicts that the building is hotter than the transformer. It is also possible that the lack of cooling is due to the effects of the initial conditions: see section 5.3 for further discussion of this possibility.

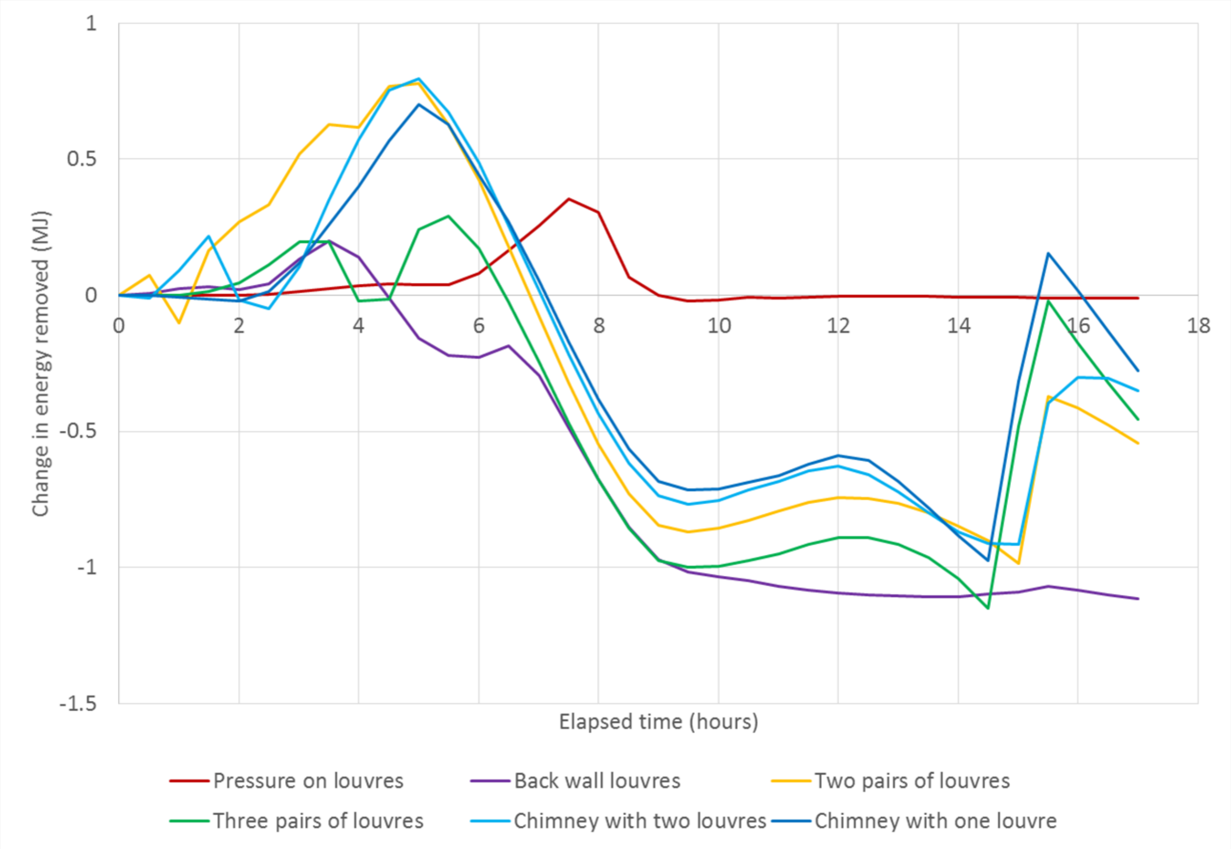

Figure 36: Comparison of changes in energy removed for the altered brick buildings.

Figures 37, 38 and 39 show the air temperature and flow direction after nine hours elapsed time for the cases with one, two, and three pairs of louvres. The case with a single pair of louvres (figure 37) has a near-uniform air temperature at the roof of about 310 K. The case with two pairs (figure 38) has a temperature at the roof of about 307 K, and the case with three pairs (figure 39) has a temperature at the roof of about 305 K.

These reductions in air temperature at the roof suggest that the air flow into the building is increased by the vents, but that the air is cooling the building not the transformer. In cases where solar heating of the building is less significant, it is likely that this increase in cooling would have more of an effect on the transformer. Two runs without solar heating have been carried out to test this hypothesis, one of the base case and one of the model with three pairs of louvres. The change in energy of the model with three pairs of louvres and no solar heating relative to the base case with no solar heating is shown in figure 40. Comparison of figures 40 and 36 makes it clear that the altered louvre geometry makes a more substantial difference when there is no solar heating, suggesting that the hypothesis that the solar heating makes heat removal from the transformer more challenging is correct.

This effect reinforces the conclusion from the GRP building models that reducing solar heating of the buildings will improve the ability to cool the transformer through improved ventilation alone.

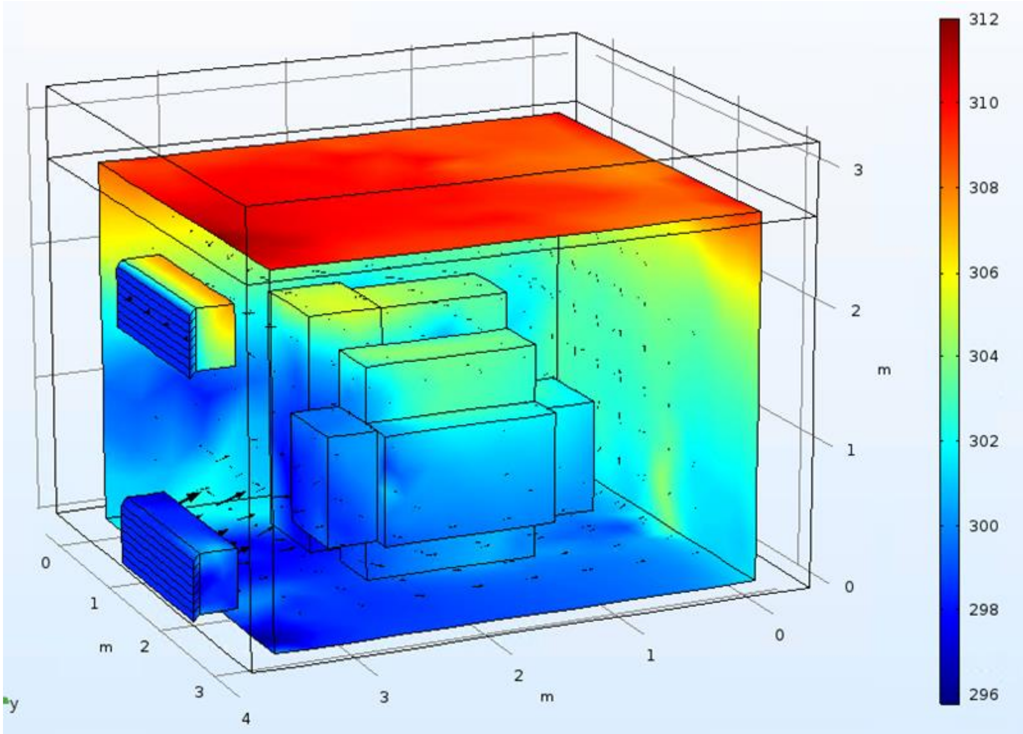

Figure 37: Air temperature and flow direction after nine hours for the base case.

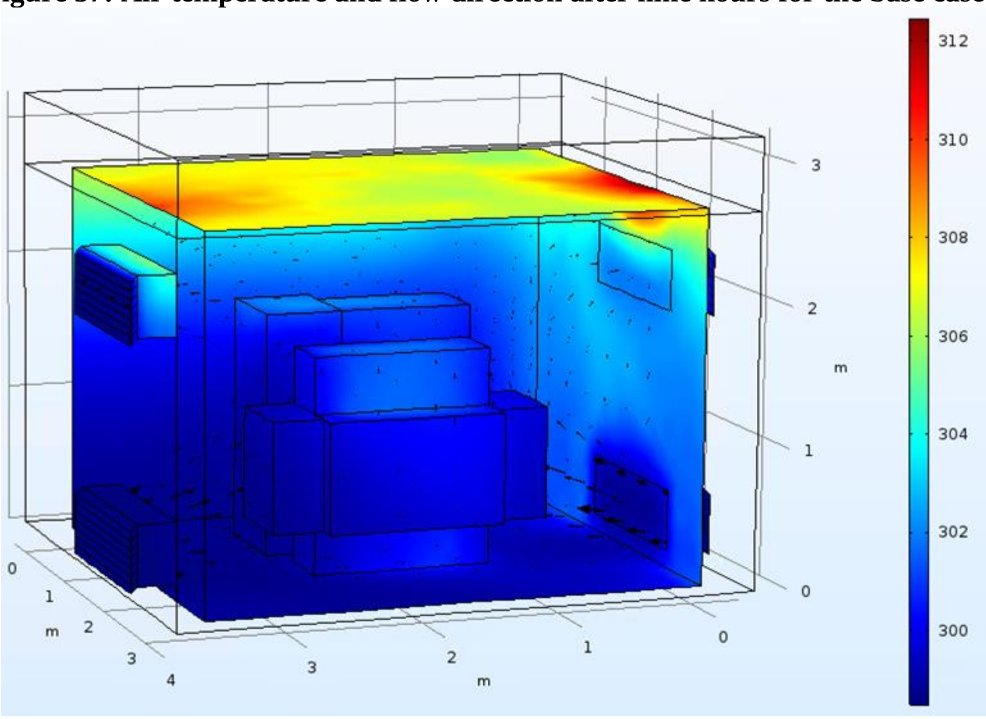

Figure 38: Air temperature and flow direction after nine hours for the model with two pairs of louvres.

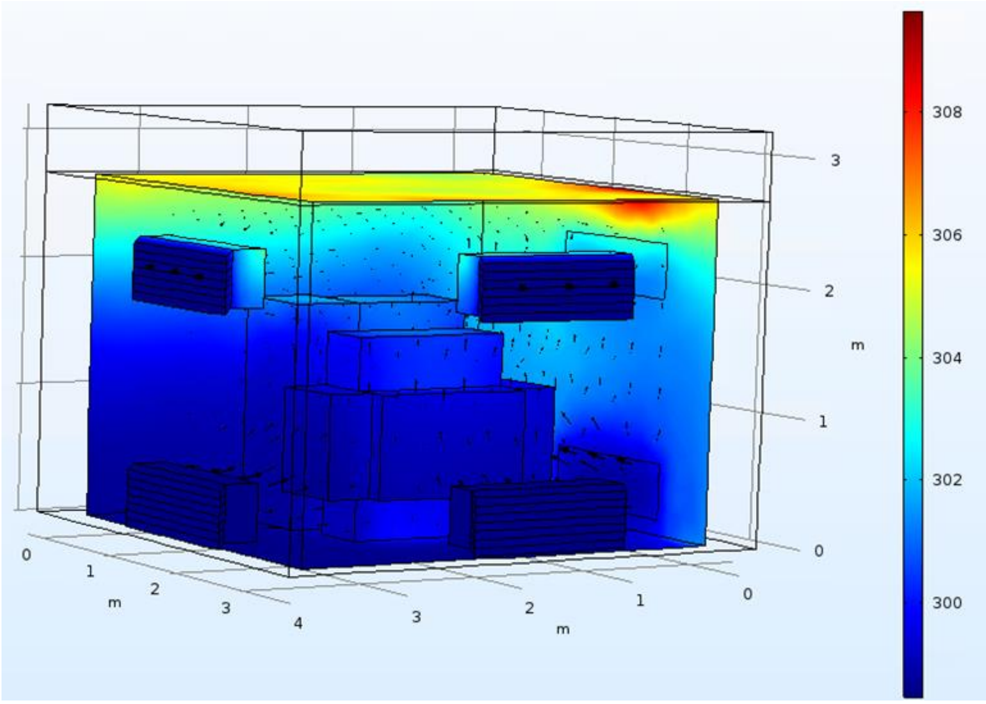

Figure 39: Air temperature and flow direction after nine hours for the model with three pairs of louvres.

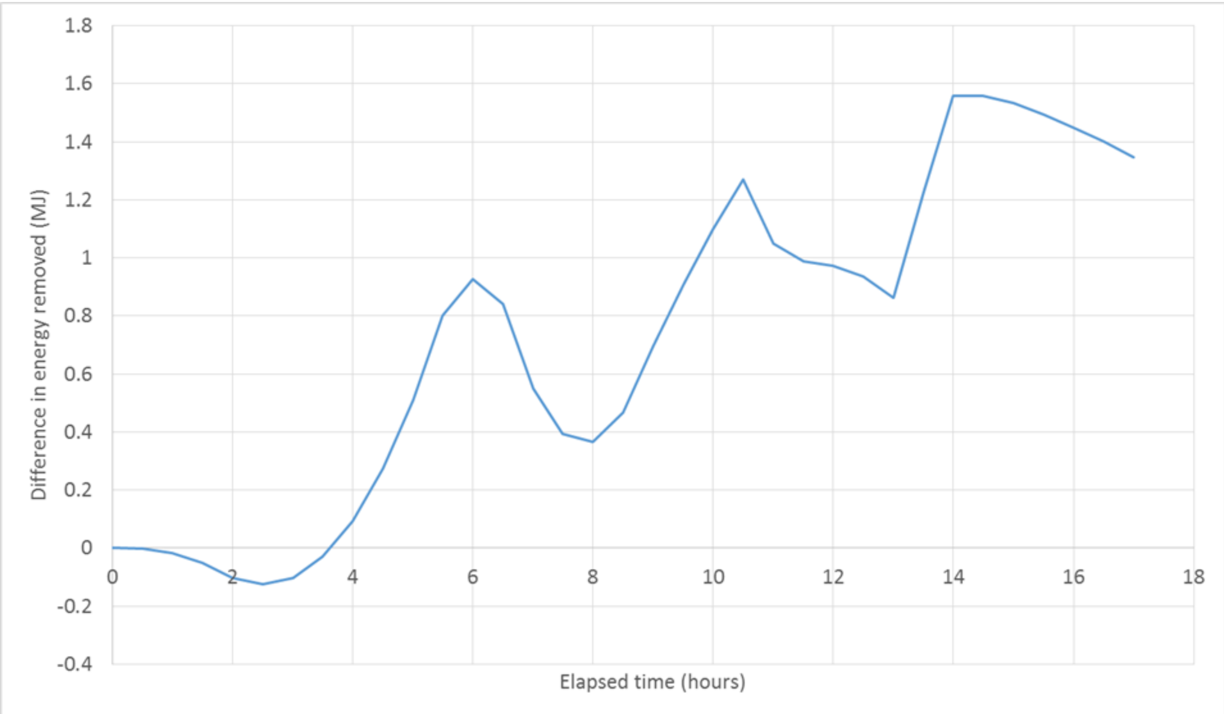

Figure 40: Change in amount of energy removed plotted against time for a model with three pairs of louvres and no solar heating relative to the base case with no solar heating. The solar heating varies between zero and its maximum value according to the curve shown in figure 4.

The maximum temperature of the surface of the transformer is plotted for the various geometric modifications in figure 41. This figure shows that extra vents reduce the maximum temperature on the surface.

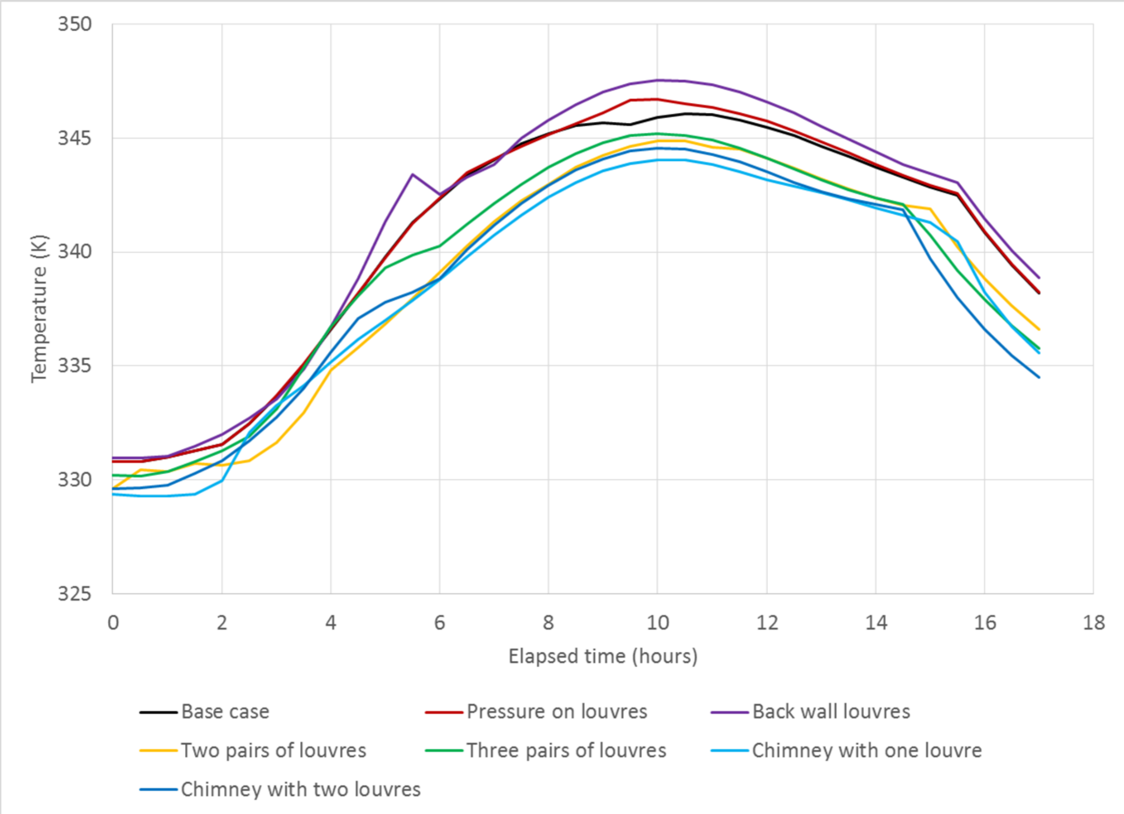

Figure 41: Maximum temperature on the outer surface of the transformer.

Figure 42 shows a comparison between the results using loose and tight spacing of the transformer and the LV and RMU cabinets. The figure shows surface temperature at different points on the transformer (locations as indicated in figure 31) for models with three pairs of louvres. There is very little difference seen in temperature. Figure 43 shows the corresponding maximum temperature of the surface of the transformer, and again little difference is seen. This lack of change suggests that the details of the spacing of the plant items does not affect the cooling. It is likely that this observation only applies to buildings where the items are in comparatively close proximity, as is the case for the new build designs.

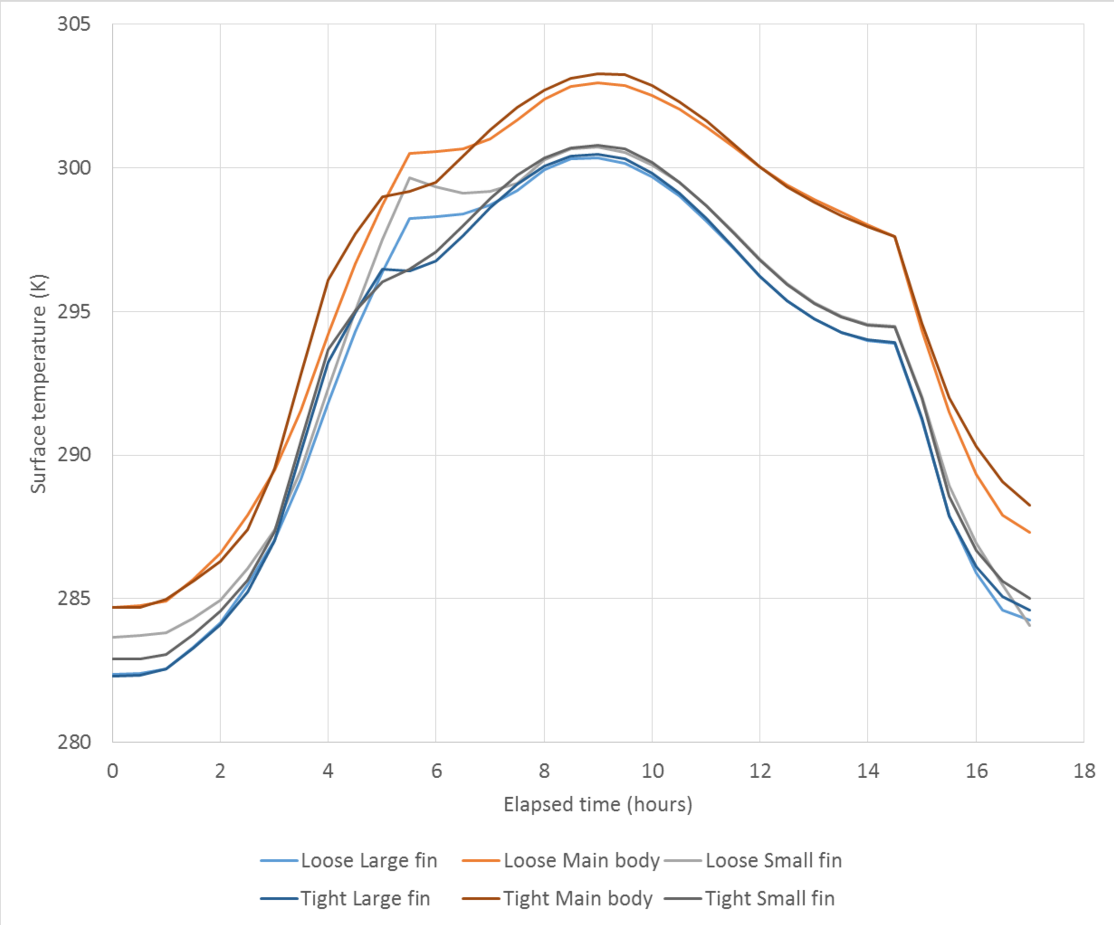

Figure 42: Surface temperature at different locations on the transformer for loose and tight plant arrangements.

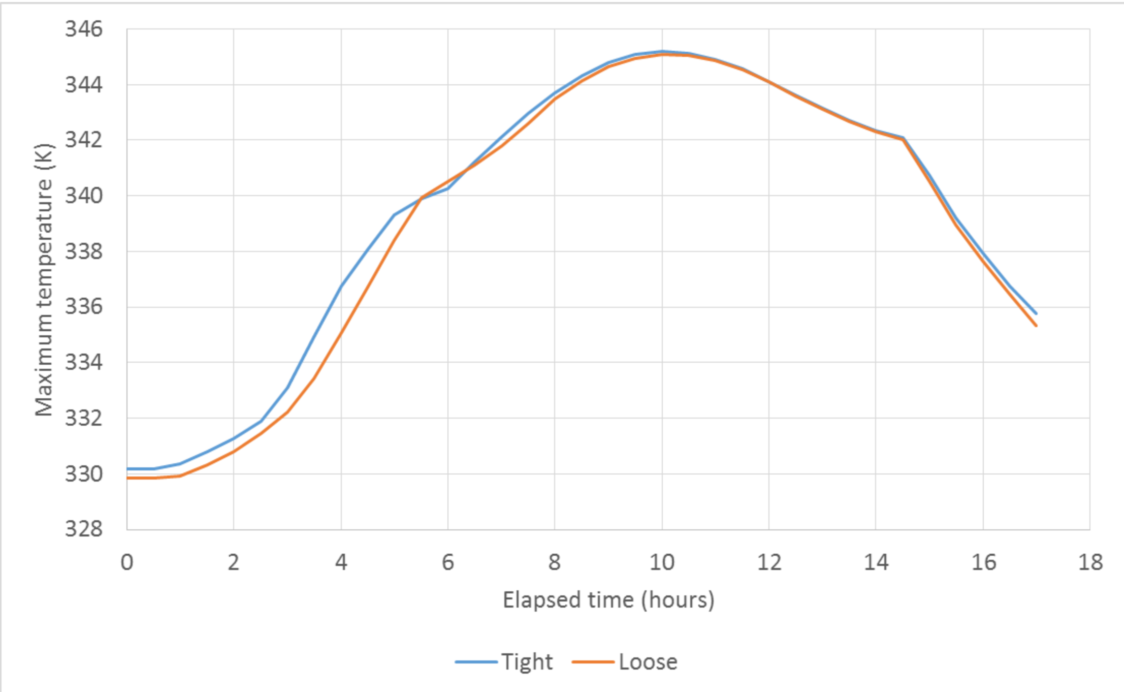

Figure 43: Maximum surface temperature of the transformer for loose and tight plant arrangements.

5.3 LONGER TIME SCALE RUNS

A set of four runs were carried out to simulate a time scale of five days. The runs were the base case for GRP and brick buildings and the geometries with three pairs of louvres for each building type.

These runs make it possible to assess, and potentially mitigate, the effects of the unknowable initial conditions. The longer runs extended the solar heating and air temperature variation curve, shown in figure 4, by assuming that a) the curve remained at its final value between 17 and 24 hours (i.e. there was no solar heating overnight and the air temperature remained fixed at its minimum value), and b) the curve repeated itself every 24 hours. The resulting variation in air temperature is shown in figure 44, and the variation in solar heating has the same variational form. The heat flux into the transformer was assumed to be constant at all times, so the drop in demand overnight was not considered. The transformer is therefore putting more energy into the air than would be expected in reality for a transformer loaded at that level, so air temperatures at night may be over-estimated.

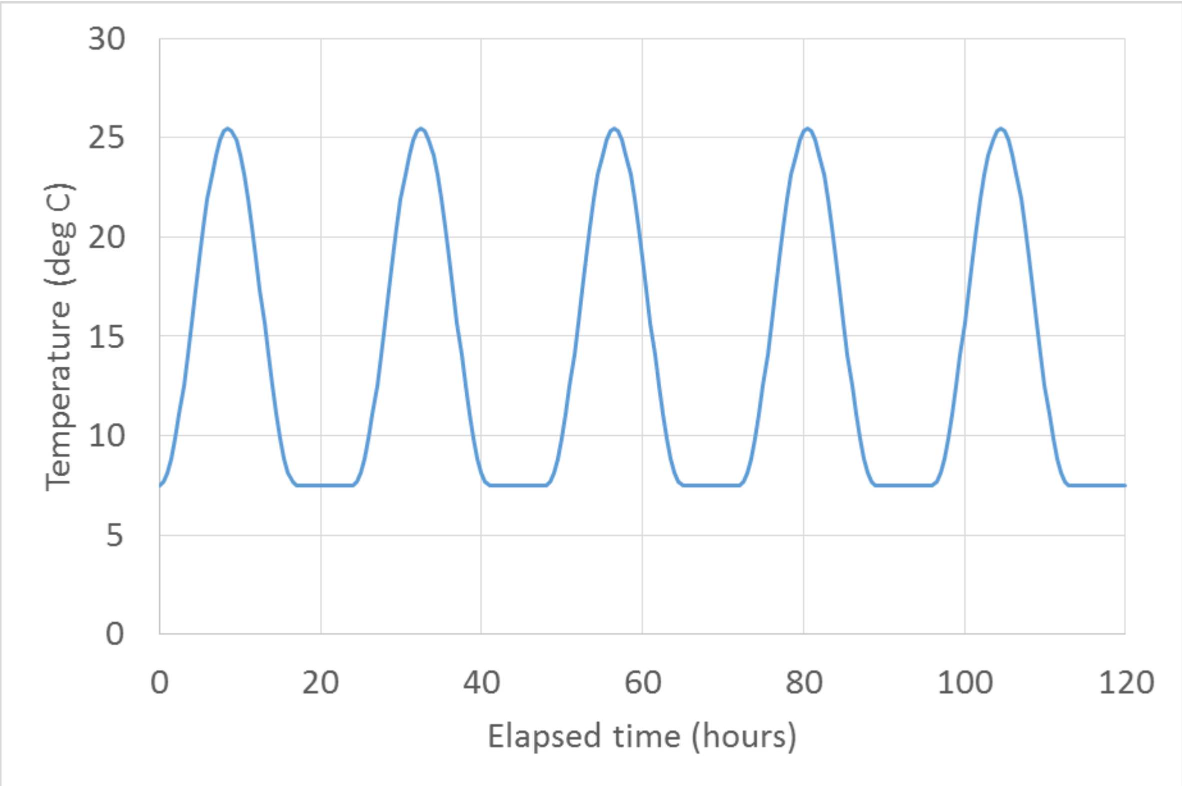

Figure 44: Variation in air temperature over a five-day period starting at 04.40 a.m. on the first day.

It was noted at this point that the air temperatures were not as specified in section 2: the air temperature should vary between 12 °C and 21 °C, but instead it varies between 7.5 °C and 25.5 °C. Additional runs of the base case for each building were carried out to examine the effects of this error.

Figure 45 shows the variation in surface temperature at a set of points on the transformer for the brick base case run. This variation is typical of all of the models (GRP and brick) and all of the results: the behaviour over the first day is slightly different from the following days, but the following days are virtually identical. The air velocity results show similar features: there is a small difference between the first two days, and the subsequent days are near identical. This similarity suggests that the first day is fairly representative of the long term behaviour, and so the models reported in the previous sections can be taken as representative of the true behaviour.

Figure 46 shows a plot of the maximum temperature within the building structure (i.e. the brick and roof temperature, not the air temperature) over the five day period. This figure shows the same lack of day to day variation as figure 45, suggesting that the effects of a sunny day on the structure are removed overnight. Hence it is reasonable to consider a single day in isolation.

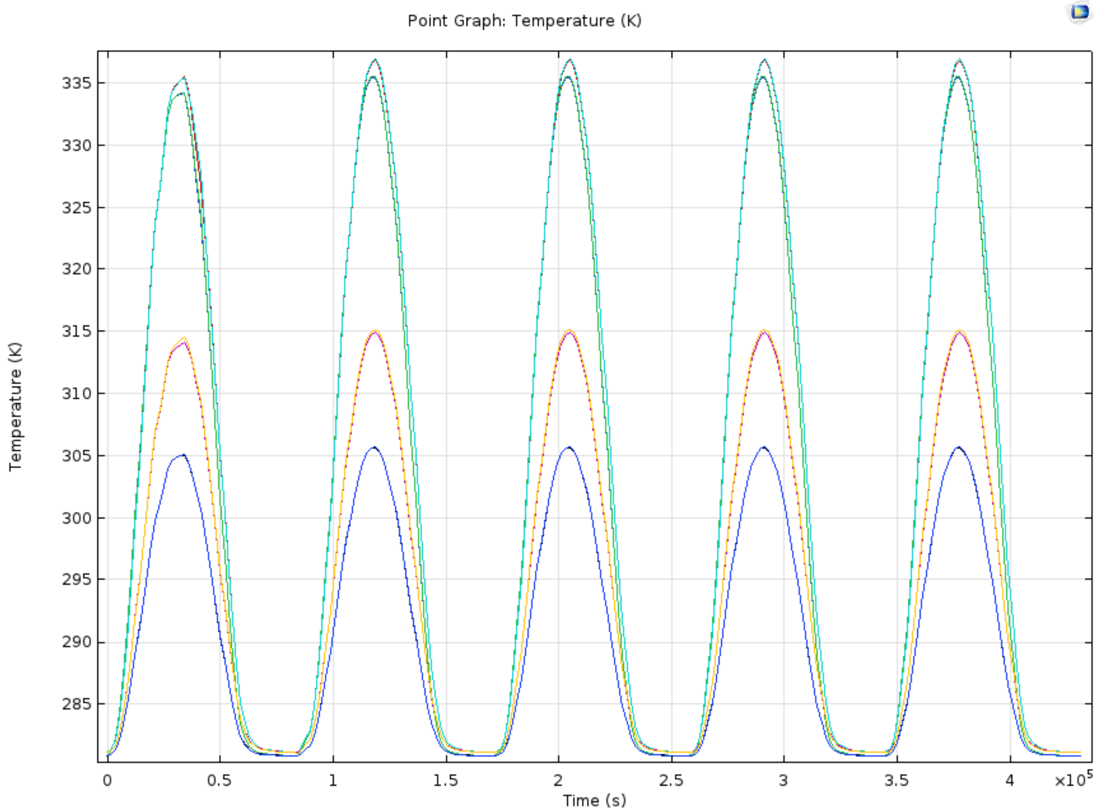

Figure 45: Variation in surface temperature of the transformer for the brick base case over a five day period.

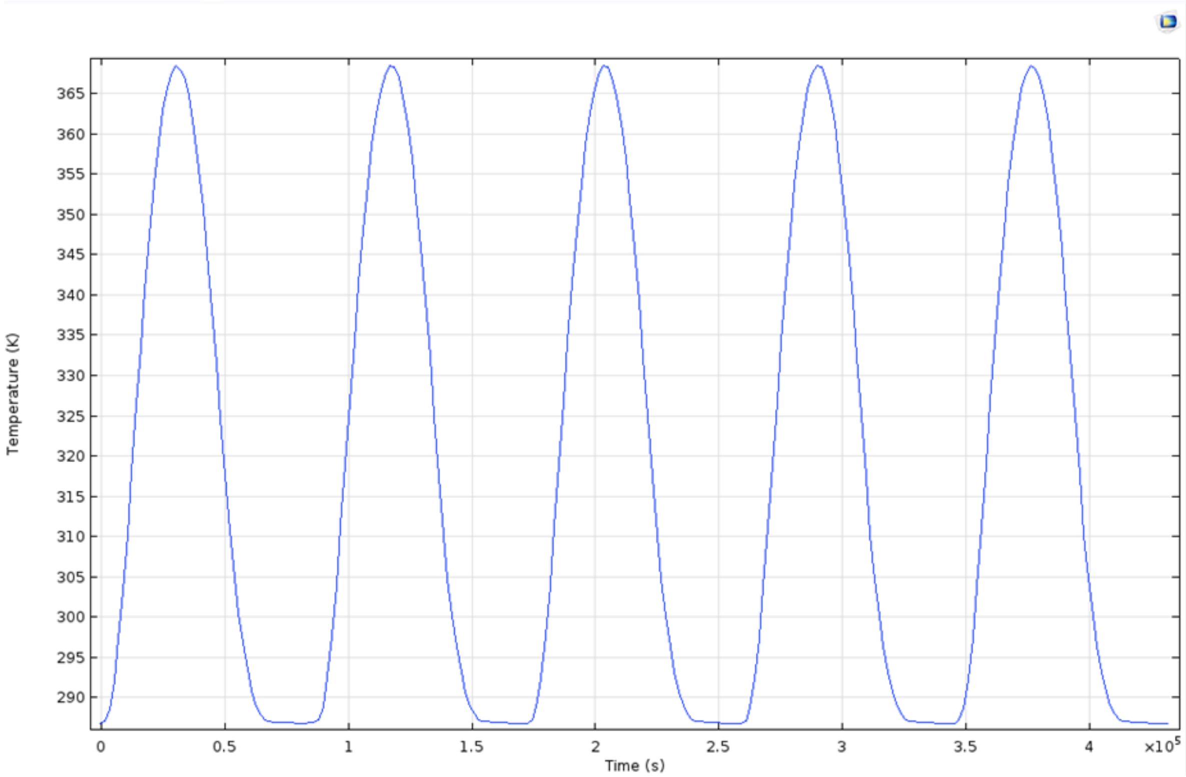

Figure 46: Variation of the maximum temperature of the brick building structure over a five day period.

The comparatively small difference in temperatures has a larger effect on the calculated energy removed. Figure 47 shows the calculated change in energy removed for the GRP and brick buildings where the model results for the first 24 hours are discarded. These results were calculated as follows:

- The rate of energy transfer from the transformer to the air at each output time step is calculated directly from the source terms representing convection from the main body of the transformer and from the fins. This calculation results in a total power at each time step.
- The total power is assumed to be constant over the output time period and is therefore multiplied by 1800 s (the duration of the output time steps) to give an energy transferred over that period.
- For all time steps after the first 24 hours, the energies over each time step are summed to give a cumulative value of energy transferred over elapsed time.
- The base case energy transferred is subtracted from the calculated transferred energy for that case, to highlight the change in energy transferred that the alteration has produced.

These results indicate that the effects of the initial conditions have led to an underestimation of the effects of the altered louvre placement, suggesting that the proposed changes will be effective. The effects are more significant for the GRP building than the brick building, probably due to the effects of solar heating on the brick building as discussed above.

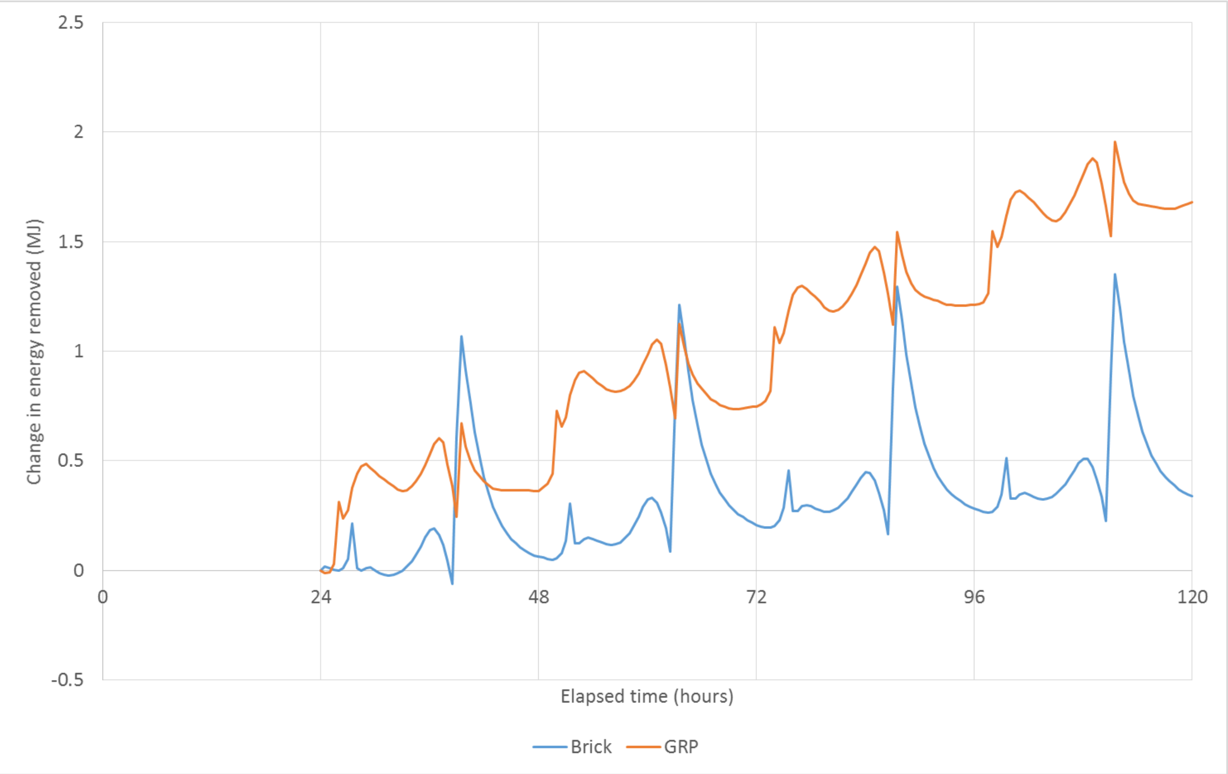

Figure 47: Change in energy removed for the last four days of the five day period.

Finally, the effects of the errors in specification of the air temperature were examined for the brick and the GRP buildings, using the base case models run over a five day period for both buildings. For both buildings, the air flow patterns remained the same, as did the relative temperature distributions. Figure 48 shows a comparison of the maximum surface temperature of the transformer for the corrected and original air temperatures. The temperature variation is the same shape, but the minimum temperature for the original air temperatures is lower, as would be expected. The differences in the minima are about 4.5 K, which is the size of the correction applied to the air temperature. Figure 49 shows the equivalent plot for the GRP building, which shows similar behaviour.

The qualitative behaviour for the corrected temperatures is similar to that of the original temperatures, suggesting that the conclusions drawn from the model results with the original temperatures are valid for the models with corrected temperatures as well.

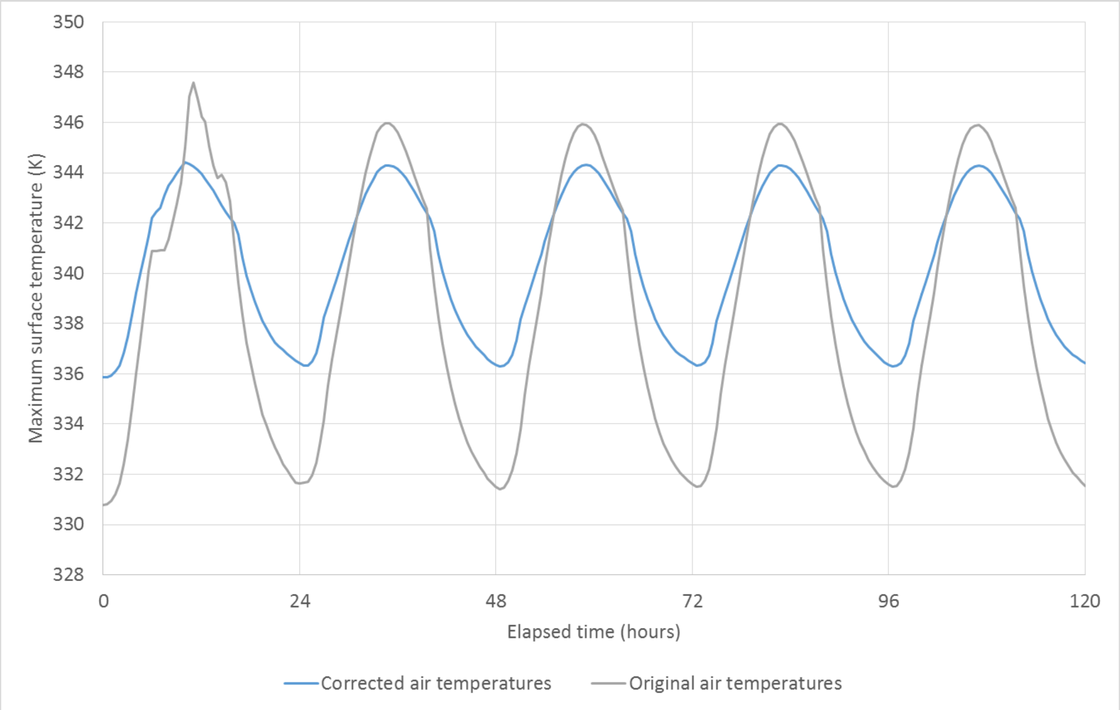

Figure 48: Comparison of maximum surface temperature of the transformer for the original and corrected air temperatures for the brick building.

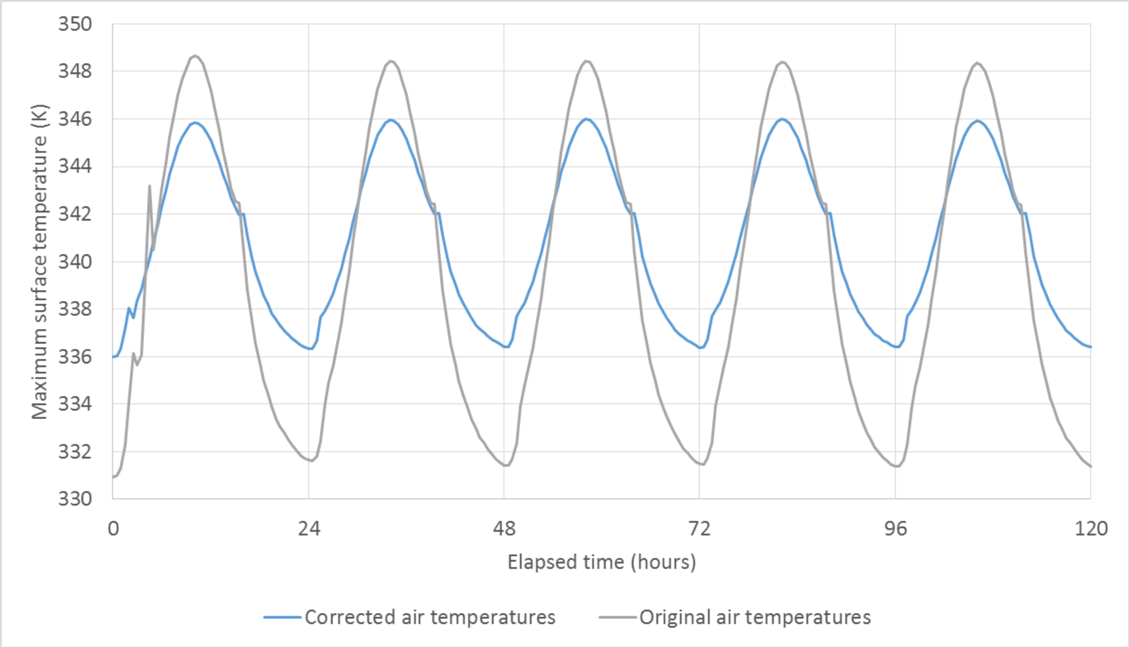

Figure 49: Comparison of maximum surface temperature of the transformer for the original and corrected air temperatures for the GRP building.

6 CONCLUSIONS & RECOMMENDATIONS

The introduction of extra louvres above the louvres in the original GRP design enhances air flow through the building. The addition of a chimney with louvres also increases the air flow through the building to a slightly lesser extent. Both alterations also reduce the surface temperature of the transformer in all locations, and increase the amount of energy removed from the transformer. The use of three louvres (two low on the side walls, one high on the back wall) also provides effective cooling, but produces hot spots on any areas of the transformer that the cold air does not reach. Ideally low louvres should be placed such that they supply cold air to both sides of the transformer.

The heat transfer within the brick buildings is strongly affected by the solar heating. The air that enters the buildings cools the building more than it cools the transformer, so that a model including solar heating does not show much change in energy removed from the transformer when extra louvres are added. A comparison of the base case without solar heating to a case with extra vents without solar heating (as in figure 40) shows that the extra louvres have a significant effect on the cooling of the transformer on cloudy days.

In general, chimneys do not seem to offer significant benefits over standard louvres, and are presumably more costly to install and maintain. It may be that chimneys are more useful as part of an active cooling approach: only passive cooling has been considered here.

The recommendations for new buildings are therefore:

- Ideally, each wall should have a pair of louvred vents on it, placed as close to the transformer as possible.
    - Using pairs of vents means that air can get in and out easily.
    - Putting vents on each wall ensures that air flow is favourable no matter what the wind direction is.
    - Placing the vents close to the transformer ensures that the cold air impinges onto the transformer.
- In cases where not all walls are accessible, a pair of vents should be placed on all walls that are accessible.
- Direct solar heating should be minimised, particularly for the brick buildings. Whilst sunny days may not be frequent, they result in a reduction in the cooling of the transformer.

The results reported in section 5 were not generated with the agreed air temperature distribution. Instead a distribution with a higher maximum and a lower minimum was used. Extra simulations with the corrected temperatures have shown that this does not affect the air flow and hence would not affect which cooling mechanism is most effective. All runs can be repeated with corrected temperatures if required.

7 REFERENCES

[1] "Celsius project thermal modelling phase 1: Modelling the heat flow in transformer substations", L Wright and J Pearce, NPL Report ENG66, 2017.

[2] "GVA/15 CIBSE Guide A: Environmental Design", Chartered Institution of Building Services Engineers (CIBSE), 2015.

[3] https://www.metoffice.gov.uk/public/weather/climate/gcw2hzs1u