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CFD AND MULTI-ZONE MODELLING OF FOG FORMATION RISK IN A NATURALLY VENTILATED INDUSTRIAL BUILDING

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ABSTRACT

Natural ventilation systems for industrial buildings have traditionally been designed using empirical engineering models, which often require the designer to 'over-engineer' the design to achieve a 'guaranteed' level of ventilation performance. This paper describes an application of computational fluid dynamics (CFD) and multi-zone thermal and airflow modelling to analyse the effectiveness of natural ventilation in removing moisture from a red mud filtration building used in the alumina industry in Australia. Our modelling work was divided into three stages: estimation of heat and moisture sources; modelling flow patterns and moisture distributions in the existing system; and finally modelling of the flow patterns and fog formation risk in a proposed new system. It is concluded that the CFD and multi-zone modelling approaches can be applied for ventilation design of industrial buildings, but great efforts are needed to collect crucial data such as heat and moisture sources in a realistic building.

KEYWORDS

Moisture transport, ventilation, CFD, multi-zone modelling, fog formation, condensation.

INTRODUCTION

Many industrial buildings in Australia utilise natural forces to provide fresh air and remove heat and pollutants that are generated in various processes. Examples of these buildings include smelters, tankhouses and potrooms. These buildings generally have the following features. The cooling load is dominated by internal heat sources, which can be as high as 10 MW (see, for example, Li *et al.* 1998). In some situations, the exact magnitude of the strength of these heat sources may not be known prior to the natural ventilation design. Ridge or roof vents are generally used to exhaust the ventilation air, which enters the building through side wall openings or louvres at the bottom level. A no-wind situation is generally the worst scenario in terms of the building's ventilation and thermal performance.

Li *et al.* (1998) applied both computational fluid dynamics (CFD) and multi-zone modelling to a naturally ventilated smelter building with large openings. Multi-zone modelling methods use the simple Bernoulli's equation and a simple power law for calculating flow rates through openings. CFD uses numerical methods to solve the time-averaged turbulence governing equations, with appropriate boundary conditions. The most important conclusion was that although the two methods generally predicted the overall ventilation flow rates fairly closely, the multi-zone method could predict a much lower neutral pressure level in the smelter building. There are many literatures on applying CFD in large enclosures, e.g. Heiselberg et al (1998) and Philips and Goodfellow (1998).

As an extension to Li *et al.* (1998), the present paper will compare CFD and multi-zone modelling in analysing moisture dispersion in an existing naturally ventilated industrial building. In particular, the fog formation risk is predicted. Both heat and moisture source strengths were unknown prior to our simulation. The analyses include heat and moisture source estimates, modelling of flow patterns and moisture distributions in the existing system, and finally simulation of the new suggested system. It is hoped that the practical procedure described in this paper will be useful to other similar applications.

THE BUILDING

The building simulated is located in Western Australia. It is divided into two main areas – the lower filtration zone and the upper penthouse (see Figure 1). The total volume of the lower filtration zone and the penthouse are about 83,000 m^3 and 6,000 m^3 respectively. In this building, a large amount of saturated vapour as well as condensation results from the industrial processes. During winter, fog is formed, which causes poor visibility. Condensation on building structures also leads to corrosion.

The existing building is naturally ventilated. The existing free opening areas for different vents are summarised in Table 1.

Due to the lack of data about heat and moisture sources, the heat and moisture generation rates in the building were estimated from monitored environmental data. The estimates were then partly checked by analysing the energy and mass balances of the various processes used in the building. Temperatures and relative humidities were monitored at a large number of grid points in the building for a period of more than a year. Weather data was also monitored on the site.

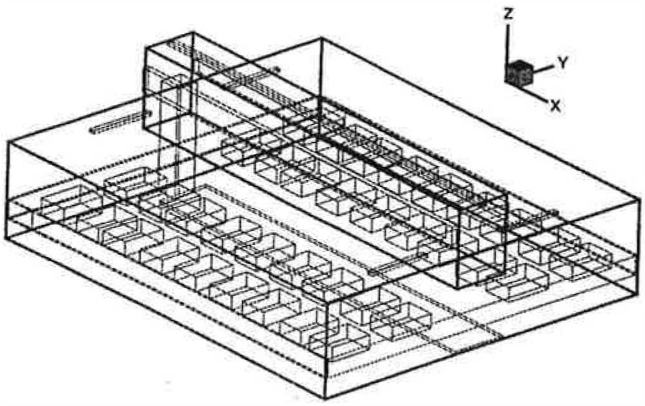

Figure 1: A sketch of the building analysed with the existing natural ventilation system

TABLE 1
FREE VENTILATION OPENINGS IN THE EXISTING BUILDING

Zone	Openings	Free area (m^2)
Low filtration zone	Louvres	341
	Roof vents	84
	Floor	90
Penthouse	Louvres	234
	Ridge vents	114

The building was divided into two zones. A multi-zone program was used, which simultaneously calculates indoor temperatures, airflow rates and relative humidity in each zone as a function of outdoor conditions, the properties of the building structure and the magnitude of indoor heat and moisture sources. CFD is a very expensive approach for the analysis at this early stage, as a significant number of simulations are needed. Predicted and measured indoor air temperatures and humidity over a chosen period, e.g. 10 days, were compared. Heat and moisture generation rates were estimated by adjusting the assumed indoor heat and moisture gains until reasonable agreement was reached.

The uncertainty in the estimated heat and moisture sources was very difficult to predict. The accuracy of these estimates depends on the accuracy of the measured data and the estimation of the free opening areas in the existing building. In the upper region of the penthouse, very little reliable monitored data was available and thus the uncertainty in the heat source estimate for the penthouse was much higher than for the low filtration zone. Thus, we chose to take a slightly conservative estimate, which means that a higher ratio of moisture to heat generation is considered. Our final estimated heat and moisture sources were 2.5 MW and 6,000 kg/hour in the low filtration zone, and 0.5 MW and 4,000 kg/hour in the penthouse.

ANALYSIS OF THE EXISTING SYSTEM

The purpose of analysing the existing system was to identify the main causes of fog formation in the building on a winter morning. Thus, a set of extreme winter outdoor conditions was chosen, i.e. an air temperature of 5°C at a relative humidity of 97%, with no wind.

A typical flow pattern predicted by CFD is shown in Figure 2 for a vertical section in the middle of the building. Thermal plumes are formed over various heat sources. Fresh air flows into the building from the lower wall louvres and floor openings, and leaves through the roof openings and the louvres in the penthouse. There are also some inflows of air through the wall louvres in the upper penthouse.

Predicted spatially averaged air temperatures and humidities in the buildings are summarised in Table 2. Similarly to Li *et al.* (1998), the two modelling methods predicted a similar overall ventilation flow rate of around 500 m^3/s (20 ACH). The air temperature rise as a result of the heat generated in the low filtration zone is about 4°C. The air temperature in the penthouse is about 1°C above that in the low filtration zone. These predicted air temperatures were in good agreement with the monitored data.

Apart from the lower region of the low filtration zone, all other upper regions including the penthouse recorded 100% relative humidity. However, there is a difference here. In the penthouse, the air is over-saturated, while in the low filtration zone, the relative humidity is about 100%. In the low filtration zone, the increase in the moisture-carrying capacity of the air as a result of the sensible heat generated almost matches the moisture generation. This means that apart from some isolated regions, no fog is formed in most parts of the low filtration region. However, as there is some uncertainty in the source estimate, the result cannot be interpreted as indicating that no fog will be formed. Thus, we still preferred to consider 100% relative humidity as indicating a high risk of fog formation.

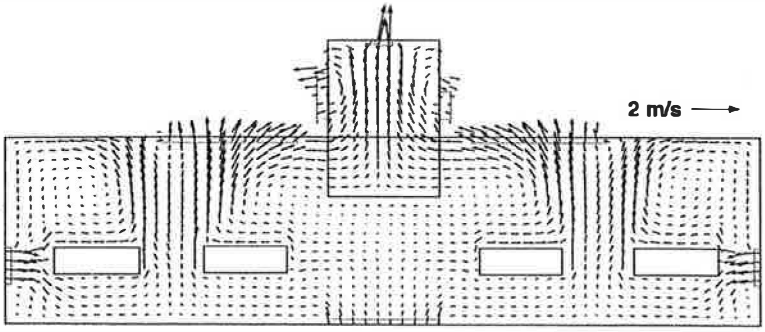

Figure 2: Velocity vector plot at a middle vertical section

TABLE 2
PREDICTED AIR TEMPERATURES AND RELATIVE HUMIDITIES IN THE EXISTING SYSTEM

	Low filtration zone		Penthouse		Overall ventilation rate (m^3/s)
	Temperature (°C)	RH (%)	Temperature (°C)	RH (%)	
CFD	9.4	97	10.0	100	471
Multi-zone	8.9	100	9.9	100	490

In the penthouse, there is a higher ratio of moisture to heat generation rate (i.e. 8.0 compared to 2.4 in the low filtration zone). The moisture-carrying capacity of the air in the penthouse is much lower than the moisture generated, thus fog is formed.

A PROPOSED NEW SYSTEM

In principle, either supplying heated air or adding more heat can prevent fog formation. There are two key constraints to be considered:

- Feasibility – the size of the building means that it is impractical to fully insulate or seal the building. Also there is obviously not an unlimited amount of energy available.
- Performance – the indoor air quality with the new system should preferably match the conditions provided by the existing system. To reduce the amount of additional heat required implies reducing the ventilation flow rate, which results in an increase in both pollutant levels and indoor air temperatures.

Four possible systems were considered.

- System 1 – natural ventilation with existing openings. Heat exchangers are used to heat up the incoming air at the lower wall louvres. The idea is simply to supply additional heat to warm up the air in the building, thus increasing the moisture-absorbing capacity of the air. The heating requirement is higher and wind can affect the system performance.
- System 2 – natural ventilation with modified openings. This system is similar to system 1, but the ventilation opening areas are reduced. Those openings most influenced by winds are removed.
- System 3 – full mechanical ventilation. This system can only be operated efficiently when the building is very airtight. Indoor air quality is poor.
- System 4 – mixed-mode ventilation. A mechanical supply system is introduced in the penthouse. The system is difficult to control and there is condensation risk associated with two merging air streams at the interface between the penthouse and the low filtration zone.

Some key performance parameters for the four proposed systems were obtained from simple psychrometric analysis and are compared in Table 3. All systems were evaluated at the same outdoor air conditions: a temperature of 10°C DB and 95% RH. The objective was to achieve an RH of 80% or less in the building.

TABLE 3
COMPARISON OF THE PERFORMANCE AND HEATING REQUIRMENT FOR FOUR PROPOSED SYSTEMS

System	Ventilation (ACH)	Additional heat (MW)	Air remperature and RH	
			Filtration zone	Penthouse
1	350	>3	22°C, 66%	24°C, 80%
2	200	1.4	26°C, 69%	28°C, 80%
3	130	1.4	27°C, 80%	27°C, 80%
4	300	2.2	24°C, 80%	25°C, 80%

The above preliminary analysis suggested that system 2 is the most economic and feasible, as there is approximately 2 MW of waste heat available on site that can be used. Apart from the ventilation design details, other design features were also needed to improve the system performance. For example, roofs must be insulated to reduce the risk of surface condensation. Following a number of multi-zone and CFD analyses, the designed ventilation openings were obtained and are listed in Table 4. In the final recommendation, an additional 2 MW of heat was suggested to be supplied to the low filtration zone in winter. Figure 3 shows some predicted velocity fields in the building with the new system. Both CFD and multi-zone analysis confirmed that the proposed new system will eliminate the fog formation problem if the heat and moisture sources estimated are realistic.

TABLE 4
FREE VENTILATION OPENINGS IN THE PROPOSED NEW DESIGN

Zone	Openings	Free area (m^2)
Low filtration zone	Louvres	90 in winter, 180 in summer
	Roof vents	0 in winter, 130 in summer
	Floor	90
Penthouse	Louvres	0 in winter, 93 in summer
	Ridge vents	150

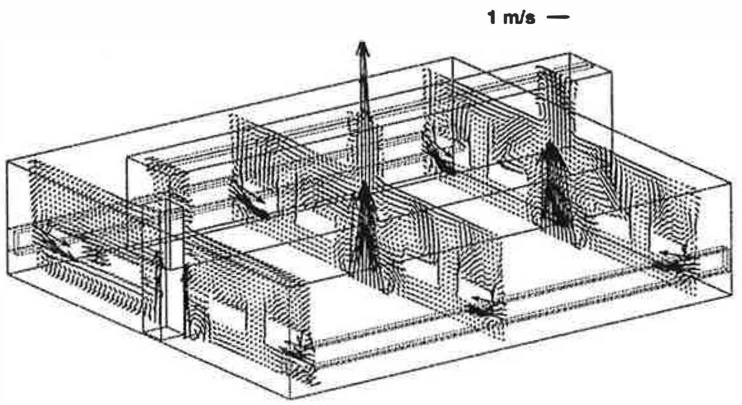

Figure 3: Velocity vector plot at three vertical sections for the new proposed system

Table 5 compares the performance of the proposed system as predicted by both the multi-zone method and CFD. Both methods predict a similar ventilation flow rate, but there are some significant differences in the predicted averaged air temperatures. This is probably due to the way that the additional heaters are simulated. Although there will not be any fog formation in the entire building in terms of the average conditions, the CFD method was able to predict that fog still exists locally in the penthouse, in a small area above the heat and moisture sources (not shown here).

TABLE 5
PREDICTED PERFORMANCE OF THE PROPOSED SYSTEM FOR WIND CONDITIONS
(10°C DB AND 95% RH)

	Low filtration zone		Penthouse		Overall ventilation (m^3/s)
	Air temperature (°C)	RH (%)	Air temperature (°C)	RH (%)	
CFD	19.3	74	21.3	90	280
Multi-zone	23.2	69	24.4	82	271

CONCLUSIONS

Both CFD and multi-zone methods have been applied to a large industrial building with a fog formation problem in winter. This project confirms our earlier findings (Li *et al.* 1998) that the *overall* ventilation rates and averaged air temperatures and humidities predicted by the two methods agree well. The practical design procedure using the two modelling approaches in this paper might be useful in other similar projects. The modelling and design work was divided into three stages: estimation of heat and moisture sources; modelling flow patterns and moisture distribution in the existing system; and finally modelling of the flow patterns and fog formation risk in a suggested new system. For this approach to be useful, it is essential to have the best information possible on the heat and moisture source strengths.

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