DESIGN AND SIMULATION OF A HYBRID VENTILATION SYSTEM WITH EARTH-AIR HEAT EXCHANGER

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ABSTRACT

This paper describes the design and simulation of a hybrid ventilation system for a recently constructed circus building in Montreal. The HVAC system draws fresh air through two underground ducts which are used for preheating or precooling. Another feature of this building is that it uses displacement ventilation. The air is supplied at low velocities (about 0.2 m/s maximum) through large diffusers behind the top level seats or under the seats. The paper describes a numerical model for the two underground ducts and a CFD study for the HVAC system. Recent measured performance data agree well with predictions; during one of the initial shows in the summer of 2004, the underground ducts provided enough cooling (plus fresh air) to keep good comfort conditions with the theatre full and without the chiller operating.

INTRODUCTION AND SYSTEM DESCRIPTION

In most locations the temperature of the soil at depths of 2 m or more varies with a small amplitude throughout the year. This provides an opportunity for passing air through long underground ducts to condition it in winter by warming it up and cooling it down in summer. This process can be particularly effective when the air is relatively dry. The soil can also be used to reject or capture heat with buried heat exchangers and a variety of heat transfer liquids.

Several researchers have studied the use of the ground for heat dissipation such as Mihalakakou, Santamouris and Asimakopoulos (1994), who developed a transient numerical model of coupled heat and mass transfer for buried pipes and validated it with experimental data. A simple steady-state analytical models to determine the temperature rise of air flowing through earth-air heat exchangers (EAHE) is described by Athienitis and Santamouris (2002).

Integration of HVAC systems with EAHE should take into account the possible variation of fresh air flow rates based on building occupancy and type of HVAC system. Displacement type ventilation systems are particularly well suited to large spaces such as the circus building concidered in this paper. They can provide large quantities of fresh air at low speeds near the audience. This supply air captures the internal gains, getting heated in the process, and rises aided by buoyancy and exhaust/return fans.

The two systems – EAHE and displacement ventilation systems were combined in the design of the Cité des arts du cirque building in Montreal (recent photo shown in Fig. 1a). The system includes

(a)

(b)

Figure 1. (a) Recent photo of Cité des arts du cirque; the cylindrical building is 23 m high with diameter 41.8 m (inlets to underground ducts can be seen in front); (b)outlet of underground duct (EAHE); tube diameter is 1 m and its grooves have radius 0.025 m; the coil can also be seen.

two 60m long, 1m-diameter galvanized steel grooved ducts (Fig. 1b) to cover a variety of loads and fresh air requirements for the circus building and offices. During shows both ducts operate while one duct operates to satisfy office loads. Figure 2 shows the principle of operatin of the HVAC system.

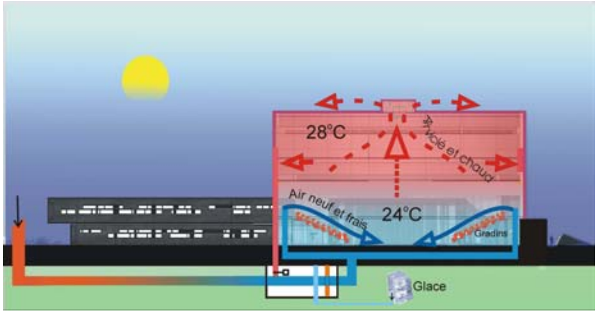

Figure 2. Schematic showing typical operation of hybrid ventilation system; fresh air is drawn from EAHE and exhausted from exhaust chimney or returns (four returns located at 17 m height).

Preliminary observations from the circus building indicate that the displacement ventilation system works as planned with maximum temperature of 25 ºC in the seated area and air velocities not exceeding 0.2 m/s. When ambient temperature is lower than 10ºC, the fans are turned off and buoyancy alone is used to displace the air using the chimney (100% fresh air). Ice storage is used to meet high cooling loads during shows.

The design of the displacement ventilation system was assisted with CFD simulations using Fluent (2002). The main aim of the simulations was to ensure low air velocities and good thermal comfort in the seated area. The paper presents typical results and discusses design issues.

SIMULATION OF EARTH-AIR HEAT EXCHANGER

If a constant and uniform temperature is assumed for the earth surface of the EAHE then an analytical relationship giving an exponential variation of air temperature with distance x from the inlet may be obtained (Athienitis and Santamouris 2002):

$$T(x) = Tw + (To - Ts)\, e^{-x/a} \qquad (1)$$

with $a = V A \rho c / (f P h)$

where Tw is the temperature of the wall of the EHAE (approximately equal to the soil temperature at that depth) and To is the inlet air temperature, which is the ambient air temperature. V is velocity, A cross-sectional area, P is perimeter of the tube, h is convective heat transfer coefficient; ρ and c are the density and specific heat capacity respectively of the flowing air, while f is a heat transfer enhancement factor to account for fins or grooves in the EAHC that increase the heat transfer area.

The heat transfer coefficient h was determined using the Dittus-Boelter correlation (Holman 1986):

$$Nu = 0.023\, Re^{0.8}\, Pr^{n} \qquad (2)$$

where Nu is Nusselt number, Re is Reynold's number and Pr the Prandtl number for air; n = 0.4 for heating and n = 0.3 for cooling.

A recent thesis (Zhao 2004) that compares several models shows that the above model is sufficiently accurate for design purposes. Comparison with experimental data by Goswami et al. (1990) given in Figure 3 indicates good agreement. While the temperature of the soil will change for continuous use over long periods, the soil temperature can be assumed to be constant for intermittent heating or cooling of several hours since the soil can recover its previous conditions during the off-period. This is close to the actual operation of the circus building.

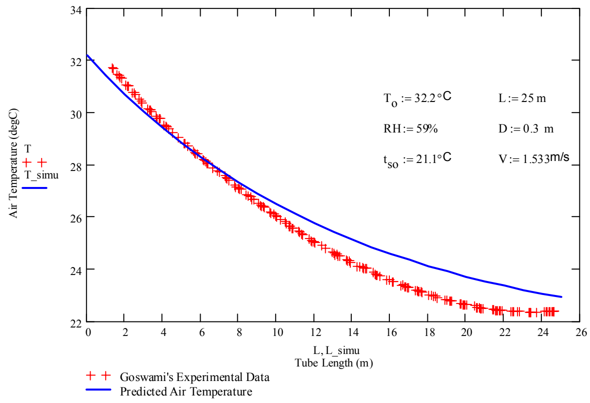

Figure 3. Comparison of EAHE model predictions with experimental data by Goswami et al. (1990) for a tube length of 25 m and 0.3 m diameter (soil temperature 21.1. C, V=1.533 m/s).

The design air flows are: 4700 litres/s of fresh air and 8500 litres/s return air for a total of 13200 litres/s. In practice the maximum airflow is never used; CO_2 sensors are used to modulate the fresh air. The system consists of two 60 m long grooved ducts with 1 m diameter. The grooves lead to a heat transfer enhancement factor f estimated to be 1.2. At the maximum flow rate the heat transfer coefficient h is approximately 12 W/m^2K. During the daytime, only offices operate (no shows) and the amount of fresh air is reduced to a maximum of about 400 liters /s. Figure 3 shows a typical temperature profile of the air in the duct in June with a soil temperature of 8.4ºC and an outside temperature of 21ºC.

Figure 4a shows a cooling situation which is the most common for the circus due to the large number of people and high internal gains. For this case we practically do not need any significant additional mechanical cooling to meet heat gains due to people (assuming a return/exhaust temperature of 25ºC). This prediction was confirmed during a show in September 2004 when the EAHE was sufficient for a show with full occupancy conditions.

A heating situation for January is shown in Figure 4b. As can be seen from Figure 4b, the air is heated by 9º ºC (from -15ºC to -6ºC) and would need supplementary heating to reach a temperature in the range 20ºC to 25ºC. In general, with full shows in the circus, the heating period would be short and would likely switch to a need for cooling due to the high internal gains.

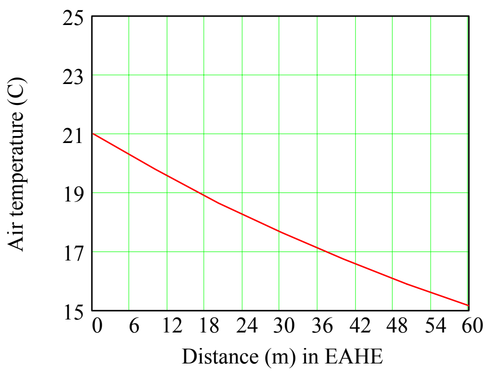

Figure 3a. Variation of air temperature in EAHE with distance from inlet (Tw = 8.4º C, To = 21ºC).

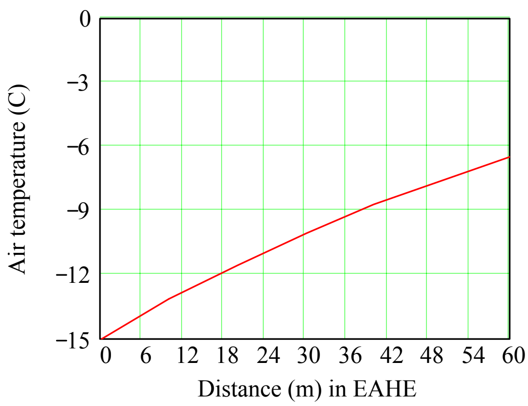

Figure 3b. Variation of air temperature in EAHE with distance from inlet in January (Tw = 3.3 ºC, To = -15 ºC).

CFD STUDY OF DISPLACEMENT VENTILATION

The main circus building is cylindrical with a diameter of 41.8 m and a height of 23 m (see Figures 1, 4 and 5). The CFD simulations were performed with Fluent (2002) and considered turbulent flow (realizable k-ε model) coupled with radiation heat transfer (radiosity model with view factor calculation). Symmetry was utilized to reduce the size of the model; in general, a quarter or half of the theatre was considered. In most simulations, half the theatre was considered; about 180000 control volumes were required for the CFD simulation (see Fig. 5).

The main objectives of the CFD study were the following:

1. To provide recommendations for sizing and locating the supply outlets as well as returns so as to eliminate high velocities (greater than 0.2 m/s) near the audience and on the stage, while ensuring good thermal comfort in the same area.

2. To size an exhaust chimney that may be used to exhaust some or all of the air aided by buoyancy when it is advantageous (mainly intermediate seasons). The chimney exhausts up to about 5000 litres/s versus the returns which collect another 8000 litres/s which is recirculated after mixing with up to 5000 litres/sec of fresh air supplied from the underground duct.

3. To investigate the behavior of the system with the chimney closed (all air returned through returns), particularly when fog is generated during shows.

Figure 5 shows sample results from the simulations for a quarter of the circus building. As can be seen, the temperature in the seated area is in the range 22℃ - 24℃ and the air velocity is less than 0.2 m/s, that is the conditions are very comfortable. The floor is warmer than the air above it due to radiant gains. The air temperature rises as expected with height due to thermal stratification. The thermal stratification given in Fig. 5a is representative of what is observed during shows with the chimney closed. In sizing the supply units the most important consideration is the maximum air velocity near the seats and the need for fresh air to reach all seated areas.

Originally, the study was performed for cooling gains of 80 kW for people and 60 kW for lights, with total airflow of about 11000 litres/s (5000 litres/s fresh air, 6000 litres/s recirculated). At the end of the study, the total load was increased and the maximum airflow was 13000-15000 litres/sec (up to 70% recirculation). During the first part of the study, air was supplied through outlets located behind the top row of seats at the back wall. At the end, with the higher load and air supply, the size of the outlets was increased to supply up to about 10000 litres/s and some air was supplied through a slot under the lowest row of seats, by distributed leakage through the seat areas, and through additional smaller outlets at the back stage (total about 3000 litres/s); all these distributed sources of supply air improve the displacement ventilation process.

The decision to locate the main supply outlets behind the seats rather than under the seats was taken because the seats will not be used in a single configuration, that is they will be movable, and it will thus be difficult to ensure reliable air distribution through them.

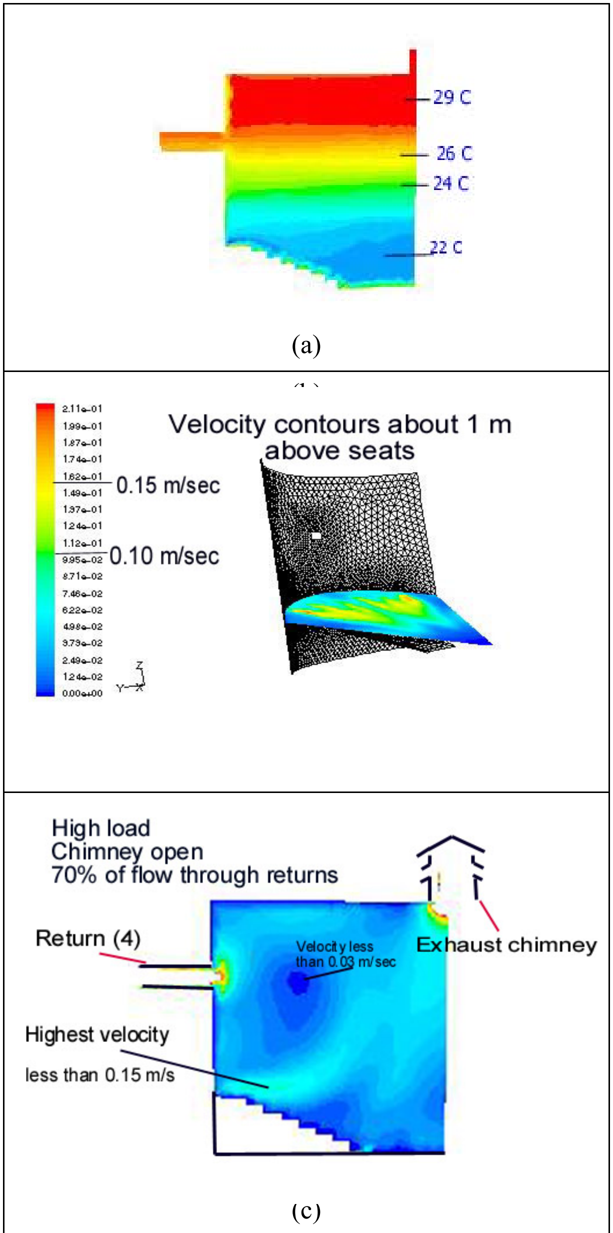

Figure 5. CFD results (a) Air temperature distribution with high loads and chimney closed; supply temperature 16°C; distribution is after 1-2 hours of high load; (b) velocity distribution over seats (c) velocity distribution in a quarter of the theatre for conditions indicated.

Figure 6 shows a cross-section of half of the circus with the chimney closed and the returns operating. The discretization grid is shown, as well as the location of the returns and supply units. The main supply outlets (26 total, each with dimensions 1.0 m x 1.15 m), are located behind the top row of seats at a height of about 5 metres, supplying air at about 0.2-0.25 m/s as required for comfort (Bauman F., 2003). The four symmetrically placed returns (each has an area of about 2 m^2) are at a height of 16 m, while the centrally located chimney has a cross-section 1.25 m x 1.6 m. The basic principle of displacement ventilation is followed, that is, cool air is supplied as near the floor as possible, it is then warmed up by heat gains from people and lights and rises to the return grilles and/or the exhaust chimney.

To study the movement of fog generated during shows (using the model of half of the theatre), oil mist particles of about 6 micron diameter, with density equal to water, were modelled as injected in the centre of the theatre and the particle trajectories were studied to determine their behaviour. Figure 6 shows the path of a typical particle over about 4 minutes. Its vertical velocity component is nearly zero, i.e. the particle is suspended and slowly deposited on a surface as expected. Because of the low velocities in the space (less that 0.2 m/sec) the particles stay suspended for a long time, creating the desired cloud effect. The average velocity of the particle shown is less than 0.05 m/sec. This was confirmed by observation of the fog generated during a show with the chimney closed, i.e. the fog appeared essentially stationary as desired in such a case.

During one of the initial shows in the summer of 2004, the EAHE provided enough cooling (plus fresh air) to keep good comfort conditions with the theatre full without the chiller operating; in particular, with an outside temperature of 21°C, the indoor temperature in the seated area did not exceed 25°C with full occupancy and the velocity was under 0.2 m/s.

CONCLUSION

A simulation study for the design of a new circus building with displacement hybrid ventilation was presented. Fresh air is supplied from an earth-air heat exchanger. In many cases, the EAHE may also satisfy all cooling needs of the building. The EAHE may also be utilized for fresh air preheating, often satisfying one-third or more of heating needs.

CFD simulations were performed to aid in sizing the supply and return units of the HVAC system, as well as an exhaust chimney that can be used to exhaust some or all of the air mainly through buoyancy. The main objective of the CFD simulations was to determine the maximum air velocity and temperature

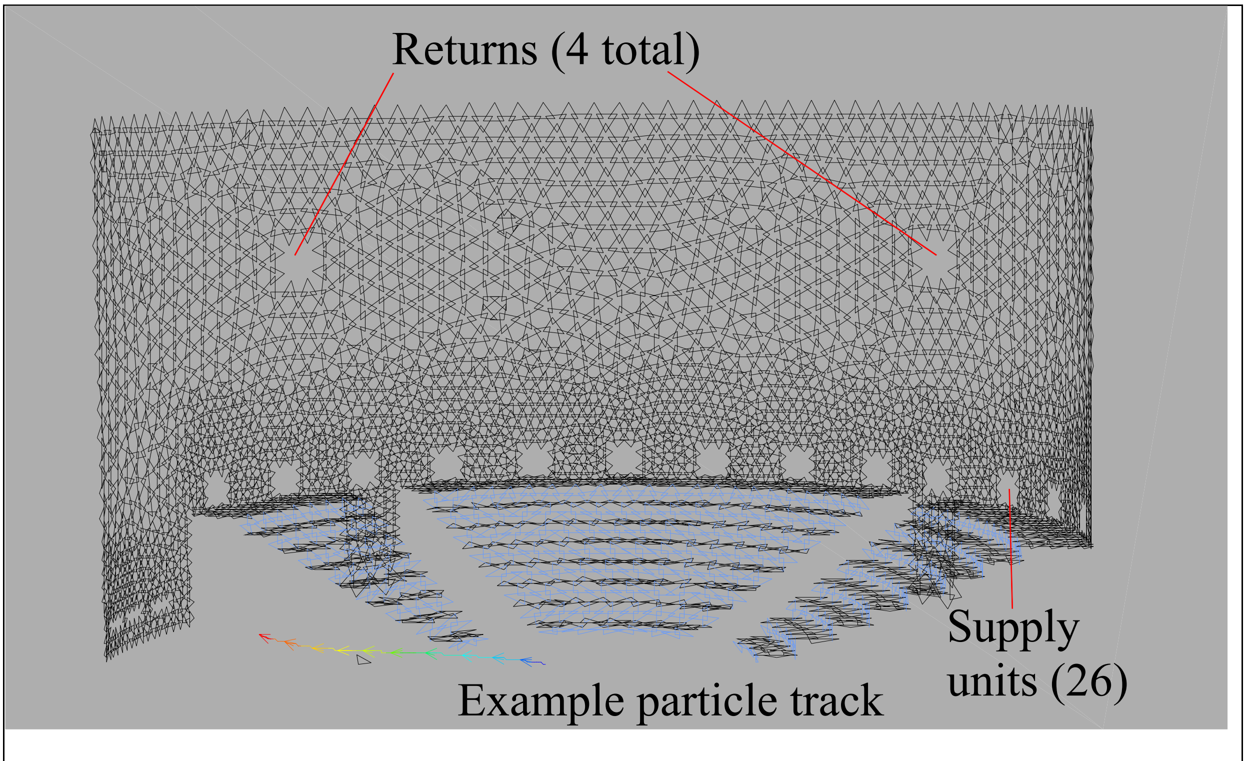

Figure 6. Discretization grid typically used for half of the circus building; returns and supply outlets also shown, as well as example particle track during fog generation for shows.

in the seated area so as to ensure good comfort conditions. Preliminary measurements from the building during a show confirm the CFD simulation predictions.

The underground ducts have been instrumented with temperature sensors attached to the EAHE tubes at different distances from the inlet and at several depths into the soil. Over the next year, the operation of the system will be studied and a more detailed transient model will be developed for the EAHE. The energy efficiency of the hybrid HVAC system will be evaluated and the velocity and temperature distribution in the theatre will be studied under the various conditions of interest such as with the chimney operating (returns closed) and part load conditions.

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NOMENCLATURE

A	cross-sectional area
c	specific heat capacity
f	area enhancement factor

D	diameter
h	convective heat transfer coefficient
L	length of tube
Nu	Nusselt number
P	perimeter
Pr	Pandtl number
Re	Reynolds number
To	outside air temperature
Tw	wall (soil) temperature
V	velocity
x	distance
ρ	density