

Comparison of Ventilation with Moist and Dry Air in the Room Connecting to a Solar Chimney

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Abstract

This research aimed to investigate the ventilation rate of solar chimneys installed under dry and humid conditions. Building models for dry air and moist air were constructed in the Computational Fluid Dynamics, ANSYS Fluent 14.0 for numerical calculation of air flow rate and air temperature within the model. This study considered time-dependent turbulent flow and results when the system approaches steady state at 3 minutes. The hot air in the solar chimney was generated by a constant heat flux of 60 W/m^2 in the chimney external wall. The dry-air models applied the Boussinesq's approximation. The species transport model was used to simulate the moisture content in the moist air. The simulation results showed that temperature of the moist air model was closer to the experiment than the dry air. The ventilation with dry air was lower than that with the moist air due to the reverse flow at the window. This research confirmed the optimum solar chimney ratio of 14: 1, similar to previous researches. In addition, the size of the opening between the building and the chimney highly affected the ventilation of the solar chimney. The best ventilation occurred in the chimney with inlet and outlet, as large as the width of the air space of the chimney.

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1. Introduction

Natural ventilation in buildings has been of interest for decades owing to increasing awareness of greenhouse gas emissions and the need for passive ventilation systems in green buildings. Solar chimneys attached to buildings are viable natural ventilation systems and could be an efficient solution. In a solar chimney, buoyancy force is created by solar radiation heating the air confined in the opened channel. Natural ventilation is achieved as warm air flows out of the chimney and fresh air flow into its connected room.

In hot and humid climates, the high vapor content in the air alters the thermal performance of solar chimneys. This is shown in previous research in a solar updraft power plant, where the buoyancy effect was applied to drive the wind turbine. Under high relative humidity where condensation was observed, the power generation became smooth and the power increased (Zhou & Cheng, 2015, pp. 619-629). Moist air in rooms ventilated by a solar chimney could behave like a mixture of water vapor and dry air. Mathematical modeling of evaporative cooling is achieved by considering heat and vapor mass transfer between the vapor source and the stream of dry air (Maerefat & Haghighi, 2010, pp. 2040–2052). Sudprasert et al. (2016) showed that simulation of standalone solar chimneys using Boussinesq's approximations provided different results from those simulated using the species transport model. With the species transport model accounting for the water vapor content in the moist air, the ventilated flow rate is 15–26% less than that simulated with the dry air model.

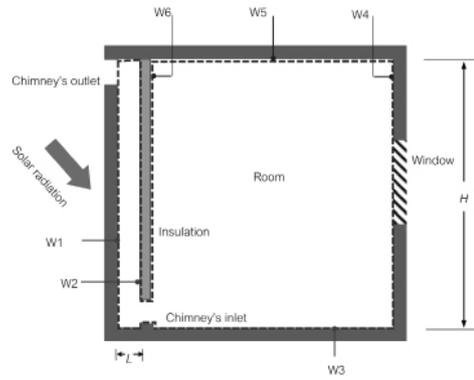
Previous research recommended a solar chimney inlet and outlet width equal to the air gap space (Gan, 1998, pp. 37-43; Hirunlabh, Wachirapuwadon, Pratinthong & Khedari, 2001, pp. 383-391). However, the optimum height to gap ratio (H/L) of a chimney diverged. The recommended H/L ratio varies from 2.8 (Mathur, J., Bansal, N. K., Mathur, S., Jain, M. & Anupma, 2006, pp. 927-935.), 11–20 (Gan, 2006, pp. 410-420) to 14 (Sudprasert, Chinsorranant & Rattanadecho, 2016, pp. 645-656). In the experiments on standalone solar chimneys, the volume flow rate increased with the increase in the chimney gap, and no optimum chimney gap was established (Chen, Bandothayay, Halldorsson, Byrialsen, Heiselberg & Li, 2003, pp. 893-906). In addition, the simulation results of a solar chimney attached to a room were 6-10% different to those of a standalone solar chimney (Khanal & Lei, 2015, pp. 217-226; Gan, 2010, pp. 1290-1300).

The purpose of the present research is to study the air flow in the room and the attached vertical solar chimney of various aspect ratios. Unlike the standalone solar chimney with constant wall temperature in the previous research (Sudprasert, Chinsorranant & Rattanadecho, 2016, pp. 645-656), the simulation models in this study integrated the building with the solar chimney, and the heat flux was applied to the chimney wall. The air flowing in the room and the window of the room were taken into consideration, and the boundary conditions in the simulation closely approximated the real situation. The 2D simulation models were created and computed using the computational software ANSYS Fluent 14.0 (ANSYS INC, 2013). The models with moist air with a relative humidity of 60% were compared to identical models simulated with dry air. The differences between the results obtained from the simulation of moist air and dry air are discussed and compared to the results adopted from previous research (Rachapradit, 2000).

2. Methodology

Figure 1 depicts the physical configuration of a 2D room with a vertical solar chimney. In this study, the solar chimney sides were opaque walls with internal surfaces W1 and W2, as shown Figure 1. The external surface of wall W1 absorbed solar radiation, which was transferred to the internal surface and, subsequently, thermal energy was transferred to the air inside the channel by natural convection. Consequently, the density of the heated air decreased and the buoyancy force developed to discharge warm air to the ambient air via the outlet at the top of the external wall. Then, room air entered the vertical air channel through the opening at the bottom of the internal wall W2, producing natural ventilation in the room and the solar chimney. The surface temperatures T_{w2} , T_{w3} , T_{w4} , T_{w5} , T_{w6} were assumed constant at 31.8, 32.3, 32.8 and 32.3 °C, respectively (Chungloo & Limmeechokchai, 2009, pp. 623-633). This assumption was applicable during the three minutes of transient simulation. The heat flux of 60 W/m² was assumed at the wall W1. This study assumed the 2D airflow across the rectangular openings where the widths of inlet and outlet openings were equal to the width of the walls.

Figure 1. Schematic of the studied model



The $k-\varepsilon$ Re-Normalisation Group (RNG) turbulence model was used to model the turbulence in the building and the solar chimney for both dry and moist air models. In the simulation of the dry-air, the usual Boussinesq approximation was employed. In the simulation of the moist air, the species transport model was used to compute the air velocity and temperature distribution in the system. For an incompressible steady-state flow, the time-averaged air flow and heat transfer equations were expressed in the following form (ANSYS INC, 2013).

$$\frac{\partial(\rho U_i \varphi)}{\partial x_i} - \frac{\partial}{\partial x_i} \left(\Gamma_\varphi \frac{\partial \varphi}{\partial x_i} \right) = S_\varphi \quad (\text{Eq. 1})$$

where ρ was the density of fluid, φ represented the mean velocity component U_i in x_i direction, turbulent parameters and mean enthalpy Γ_φ was the diffusion coefficient and S_φ was the source term for variable φ .

In the moist air models, the local mass fraction of each species (Y_i) was predicted through the species conservation equation as follows:

$$\frac{\partial}{\partial t} (\rho Y_i) + \nabla \cdot (\rho U_i Y_i) = -\nabla \cdot J_i \quad (\text{Eq. 2})$$

where J_i was the mass diffusion of species i . In this study the water vapor was species 1 and air was species 2. The density of the air-vapor mixture was computed from the ideal gas law as follows:

$$\rho = \frac{p}{RT \sum_i \frac{Y_i}{M_{wi}}} \quad (\text{Eq. 3})$$

where p was the operating pressure, R was the universal gas constant, T was the fluid temperature and M_{wi} was the molecular weight of the species i . The viscosity (μ) and thermal conductivity (k) of the air-vapor mixture were specified by the ideal gas mixing law (ANSYS INC, 2013). The specific heat capacity (c_p) was defined as a function of mixture composition, as follows:

$$c_p = \sum Y_i c_{p,i} \quad (\text{Eq. 4})$$

Simulations were carried out on the rectangular meshes with a uniform distribution. The accuracy of the numerical results was tested in a mesh independence study. Simulation results showed that the temperature distribution and velocity vectors were similar for mesh numbers of 89,480 and 126,600. In this study, the solution was assumed grid independent if the solution difference between two mesh densities is less than 5%. Hence, coarser meshes was chosen since it saved computational times and provided sufficient accuracy.

3. Results

3.1 Validation of the simulation model

The accuracy of the simulation with mathematical models was observed in Figure 2 where the simulation results were compared with previous experimental research. By modeling the same size as the one used in the Rachapradit (2000), the chimney height was 2.0 m, width 0.14 m, and the chimney entrance was 0.05 m. The surface and air temperatures at the inlet and outlet of the solar chimney were also determined by the same experiment. The moist-air model showed air temperature closed to the experimental results. Therefore, the moist-air model performed better than the dry-air model in the prediction of air temperature in the solar chimney. The higher temperature of moist air could be the results of thermal

properties of water vapor. The dissipation of heat in the water vapor was more difficult than that in the air due to higher heat capacity and lower thermal conductivity (see Table 1).

3.2 The flow patterns in the room and in the solar chimney

Figure 3 shows the dry- and moist-air velocities in the room and in the solar chimney with H/L ratio = 14:1. The results showed a stream of air flowing back to the window. This reversed flow causes less air entering the chimney. In this study, the window and the chimney’s inlet were two opposite openings so that air could leave the room via both openings. However, the reversed flow happened in the dry air model (Figure 3a) was more than the moist air (Figure 3b). The explanation relied on the difference in the flow patterns that relating to the dissimilar in properties of the dry and the moist air. Figure 3a showed that dry air entering the windows hit the internal wall and separated into two parts, the recirculating air near the ceiling and the air flowing into the chimney. The moist air in Figure 3b entering the room did not hit the internal wall because it flowed up to the ceiling before flowing down along the internal wall to enter chimney’s inlet. Only small part of moist air flowing back to the window. For the same volume and air temperature, moist air was lighter than the dry air because water vapor, a component in the moist air, was less in density (Table 1). Therefore, the moist air in the room tended to flow up and brought higher air flow into the chimney.

3.3 The effect of solar chimney aspect ratio on air temperature and flow rate

Figure 4 illustrates the contour of velocity distribution in the room and the connected solar chimney with aspect ratios 14:1, 30:1 and 10:1. For the building with dry air (Figure 4a, 4b and 4c), the reversed flows always happen at the windows in any solar chimney aspect ratio. In the dry air, the air velocities at the inlet and outlet of the chimney increased with the increase of the chimney’s aspect ratio. On the other hand,

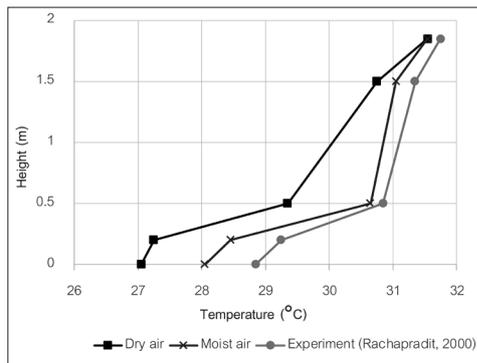


Figure 2. Comparison of temperature profile in the solar chimney

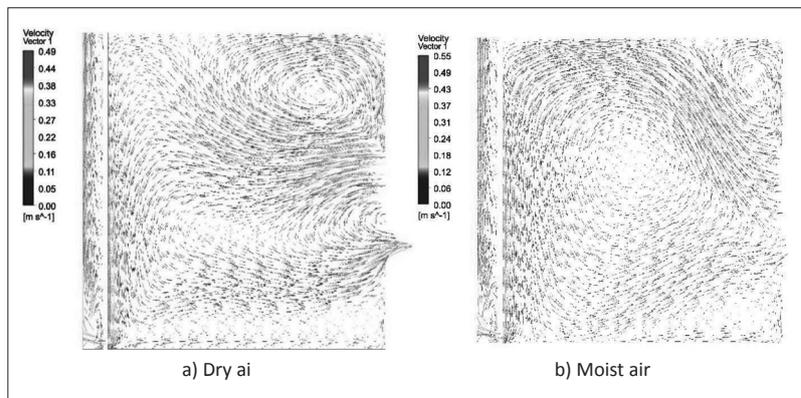


Figure 3. The velocities of dry and moist air in a building operated with a solar chimney of $H/L=14:1$

Property	Water vapor	Air
ρ (kg/m ³)	0.6794	1.092
c_p (J/kg°C)	1874	1007
k (W/m°C)	0.02032	0.02735

Table 1. Thermal properties of vapor and air at 50°C (Cengel, 2004)

the velocity of moist air (Figure 4d, 4e, and 4f) were steady, i.e. almost independent with the chimney’s aspect ratio. In this study, the height of the inlet and outlet of the chimney’s were kept at 0.05 m, corresponding to the previous study of standalone solar chimney (Rachapradit,2000;Sudprasert,Chinsorranant & Rattanadecho, 2016, pp. 645-656). It was possible that the inlet and outlet openings were too small to allow air flowed between the building and the chimney. The increase of the air velocity in the dry-air model was

the result of air fluctuation within the chimney and the outflow from the window. In the moist-air model, maximum air velocity were unchanged because moist air was restricted to flow through the inlet of the chimney. Correspondingly, the temperature of the dry air in Figure 5a, 5b, 5c reduced

with the increase of chimney's size because the velocity allowed high flow rate in the large chimney. For the moist-air models (Figure 5d, e, f), air temperature were similar for any chimney's aspect ratio due to the steady in air velocity.

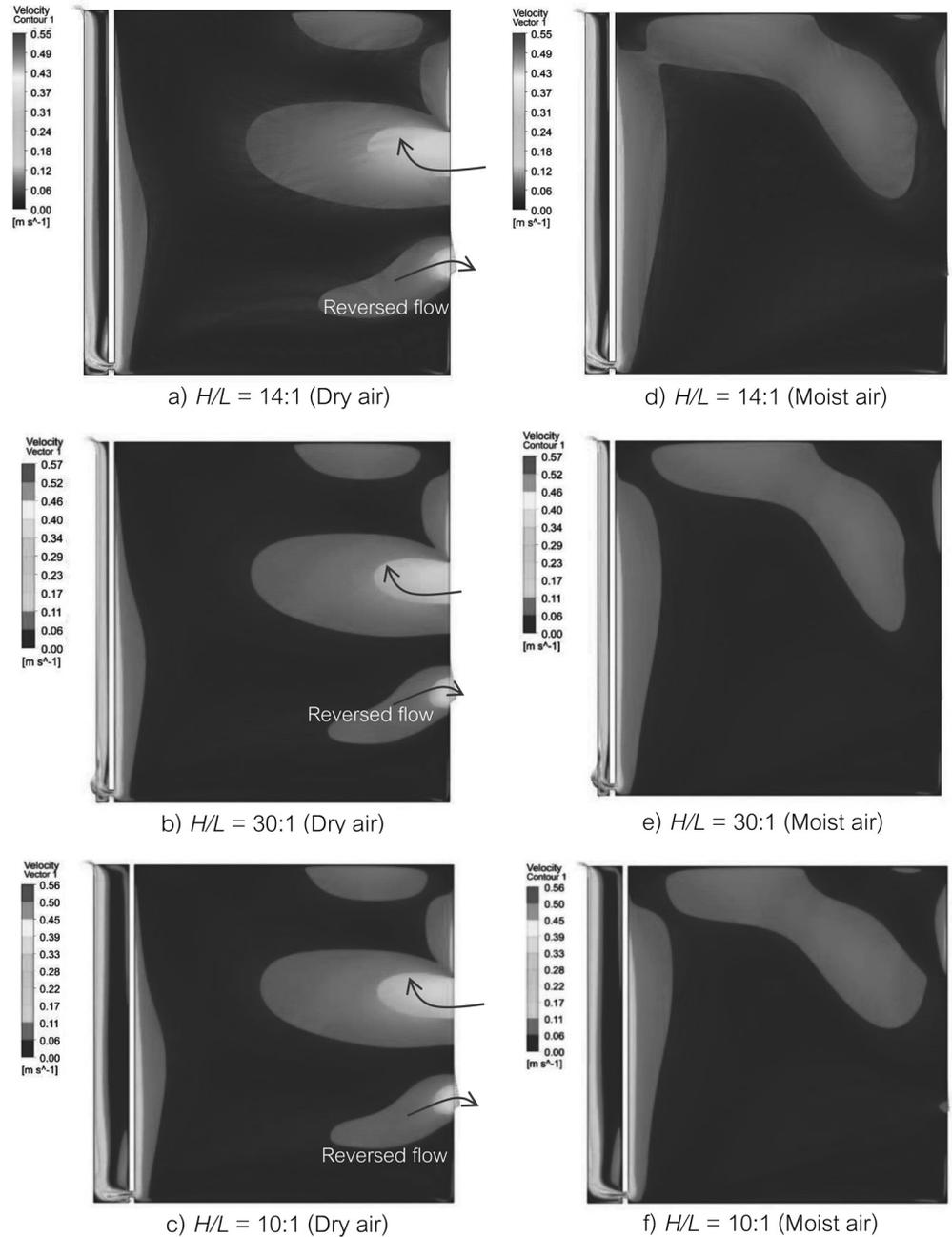
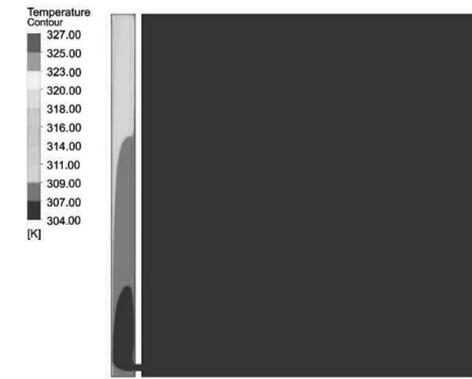
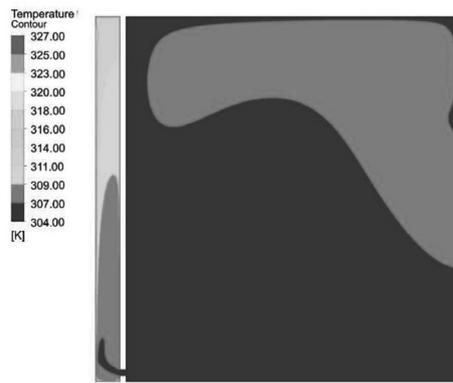


Figure 4. Velocity distribution in the building connected to solar chimney



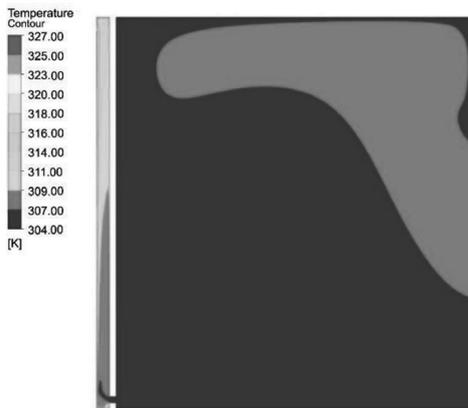
a) $H/L = 14:1$ (Dry air)



d) $H/L = 14:1$ (Moist air)



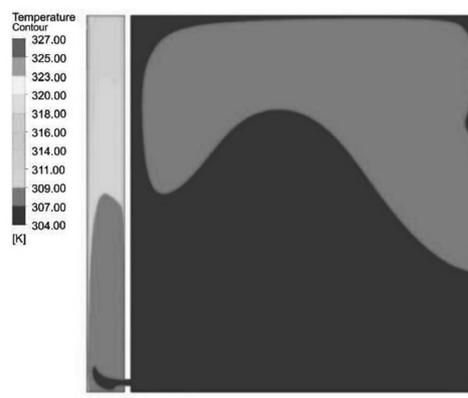
b) $H/L = 30:1$ (Dry air)



e) $H/L = 30:1$ (Moist air)



c) $H/L = 10:1$ (Dry air)



f) $H/L = 10:1$ (Moist air)

Figure 5. Temperature distribution in the building connected to solar chimney

Table 2. Average air velocity, temperature and mass flow rate in room connected to a solar chimney

Solar chimney aspect ratio (H/L)	Air type	Average air velocity in the room and chimney (m/s)	Air temperature (K)	Mass flow rate (kg/s)
14:1	Dry air	0.0441	305.0 - 328.7	0.0220
	Moist air	0.0438	305.0 - 323.4	0.0260
30:1	Dry air	0.0471	305.0 - 329.5	0.0225
	Moist air	0.0026	305.0 - 323.6	0.0276
10:1	Dry air	0.0462	305.0 - 327.7	0.0213
	Moist air	0.0473	305.0 - 323.5	0.0259

Figure 6. Mass flow rate of dry air and moist air at the outlet of the solar chimney

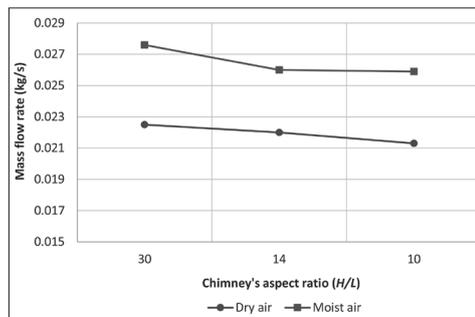
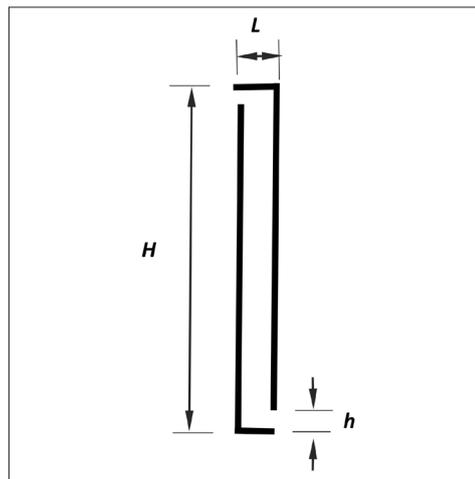


Table 2 summarizes the results of air temperature, average velocity and mass flow rate at the outlet of the solar chimneys. The mass flow rate in the solar chimney with $H/L = 30:1$ (small air gap) was higher than that with $H/L = 10:1$ and $14:1$ about 5.3-6.2%. The moist-air models showed higher mass flow rate than that of the dry-air model by 21.6-22.7%.

Figure 6 compared the results of mass flow rate of dry air and moist air. Comparing among the solar chimney with aspect ratios of 30:1, 14:1 and 10:1, that the mass flow rate reduced slightly in the large solar chimney for both dry air and moist air. From Figure 6, the optimum aspect ratio was not shown. This is caused by the too small opening between the building and the inlet of the solar chimney. The optimum aspect ratio of 14:1 was found after increasing of the opening between the building and the inlet of the solar chimney (next section).

Figure 7. The chimney height (H), air-gap space (L) and the opening height (h)



3.4 The effect of opening height on the ventilation

The limited opening height would reduce the mass flow rate and prevented the flow between the room and the connecting solar chimney. The opening height was shown as h in Figure 7. In this section, the opening height (h) was increased to be equal to the distance between the chimney walls (L), the air-gap space.

The results of increasing the opening height from 0.05 m to $h = L$ are shown in Figure 8. The effect of opening heights on air flow rate appeared for all chimney aspect ratios. In Figure 8, the solar chimney with aspect ratio of 14:1 and $h = L$ yielded the highest air flow rate.

The effect of increasing opening height (h) is investigated in detail through the velocity vectors illustrated in Figure 9 for the chimney with $H/L = 14:1$. Figure 9a and 9b are the results of the opening height (h) of 0.05 m. Figure 9c and 9d are the results of $h = L$, where $L = 0.14$ m. The increase of opening height to the air-gap space reduces the maximum air velocity for both dry and moist air. The flow patterns in the room with $h = 0.05$ m are similar to that with $h = L$. Therefore, the larger openings allows more air flow without changing the flow pattern.

4. Conclusions

This research investigated the effect of the solar-chimney aspect ratios on the ventilation using the dry-air and the moist-air models. The moist air in this study was the ambient air with relative humidity of 60% and temperature of 34°C. The dry air was the ambient air with ideal gas properties. The results in this study showed that the air circulated in the room and that left through the window of the room influenced the ventilation in the solar chimney. The solar chimney with dry air showed that the reversed flow of air at the window reduced the ventilation through the solar chimney. The effect of reversed flow on the ventilation with moist air was less than that on the dry air. The optimum solar chimney aspect ratio of 14:1 was found in the design with the chimney's openings equal the chimney's air gap.

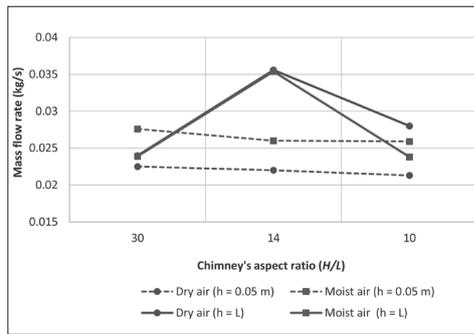


Figure 8. Mass flow rate of dry air and moist air with different opening heights

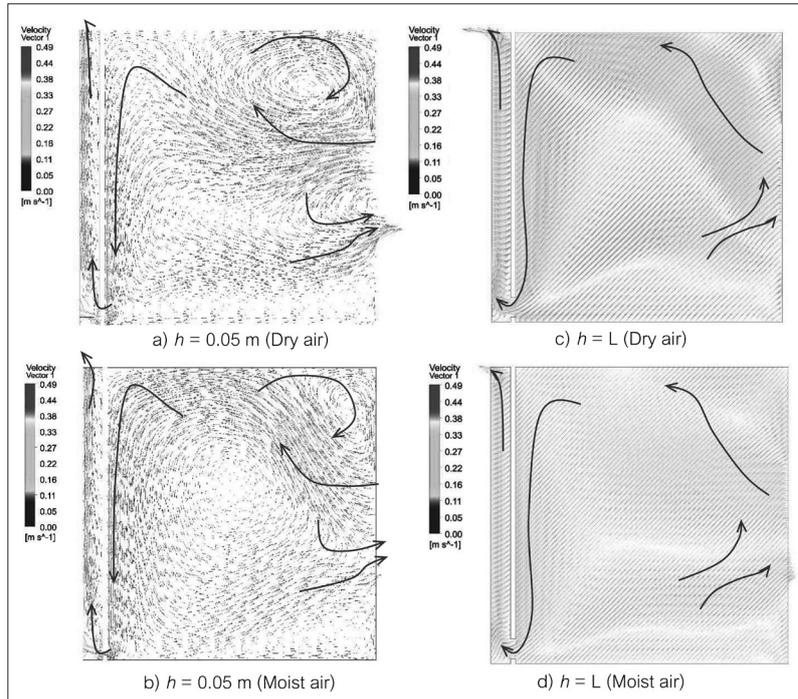


Figure 9. The patterns of air flow in the room connecting to a solar chimney with $H/L = 14:1$

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