Application of Evaporative Cooling in the Building Ventilated by a Solar Chimney

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Abstract

Over the last two decades, the interest in natural ventilation in buildings has been revived because of the growing awareness of greenhouse gas emission and the need for an efficient passive ventilation system as part of a building. In this respect, solar chimney is a promising solution. In the hot-dry climate, solar chimney has been widely studied to use with a water evaporating system to reduce air and surface temperatures in the buildings. In the hot-humid climate, several applications of solar chimney with indirect evaporative cooling were reported. Successful results were shown in air temperature reduction to meet human thermal comfort. The effect of incorporating the evaporative cooling on air velocity, volume flow rate, relative humidity and air temperature are reviewed in this study. In addition, the mathematical modelling of this integrating system are discussed.

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1. The solar chimney

The solar chimney is a passive technology that rely mainly on solar energy. It utilizes the thermo-syphoning air channel where the driving mechanism is achieved by thermal buoyancy. The solar radiation causes air temperature in the channel rise as well as a density drops. The drop of the air within the solar chimney causes the air to rise and be expelled out of the top of the chimney. A solar chimney is usually attached to a room or the building to drive the fresh air into the room. Figure 1 depicts a room utilizing a solar chimney. A solar chimney can be applied in heating but this paper presents only the cooling application. The external wall of the chimney was originally made of glazing material, however it has been constructed with opaque material in the hot-humid climate to reduce the direct solar penetrated in to the building wall.

For decade, experimental and analytical researches on solar chimney application in buildings aimed to increase thermal performance of the solar chimney. This included determination of optimum chimney aspect ratio and chimney configurations to maximize the ventilation. The recommended aspect ratio varies from 11-20 (Gan, 2010, pp. 1290-1300; Sudprasert, Chinsorranant & Rattanadecho, 2016, pp. 645-656; Wei, Qirong & Jincui, 2011, pp. 65-75). The configuration of solar chimney were vertical chimney (Sompop, Jongjit, Joseph & Belkacem, 2009, pp. 2545-2561), vertical solar chimney with inclined wall (Khanal & Lei, 2015, pp. 217-226). The field studies included thermal performance of solar chimneys in the educational buildings. In the cold climate, the stack ventilation was preferred in the winter. In the windy season, wind penetrating through the chimney and increased the ventilation in the building (Katarzyna & Andrzej, 2012, pp. 242-247).

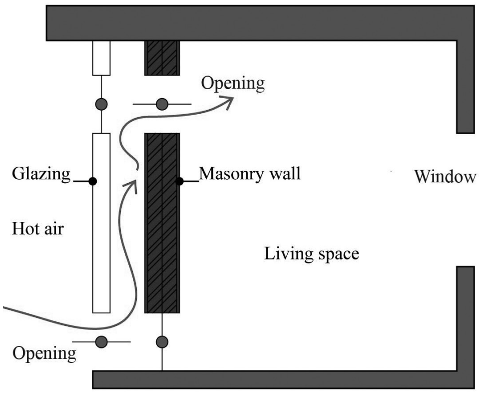


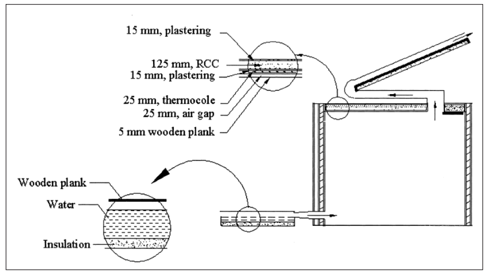
Figure 1. The application of a solar chimney to drive air through the room and the chimney. (Source: Chungloo & Pichaisak, 2011, pp. 8-19)

2. The Solar Chimney Integrated with Evaporative Cooling

2.1. Direct evaporative cooling

A comprehensive reviews of researches on direct evaporative cooling in China was found in a previous reviewed article by Xuan et al. (Xuan, Xiao, Niu, Huang & Wang, 2012, pp. 3535-3546) and the applications in buildings were found in a previous reviewed article by Cuce & Riffat. (Cuce & Riffat, 2016, pp. 1240-1249). In the hot-dry climatic condition, direct evaporative cooling were experimentally investigated and found benefit of energy saving with a satisfactory thermal comfort (Heidarinejad, Bozorgmehr, Delfani & Esmaeelian, 2009, pp. 2073-2079). In the composite climate like India, a direct evaporative cooling was installed with a solar chimney and tested for one year (Raman, Mande & Kishore, 2001, pp. 319-329). Two passive models for summer are shown in Figure 2a and Figure 2b. Figure 2a shows that the small water source was installed at the inlet of the building and the inclined solar chimney was applied on the roof of the building. This system was found inadequate to provide thermal comfort in summer. Consequently, a second passive model (Figure 2b), which consisted of a south wall collection and a roof duct cooled by a sack cloth evaporative cooling system was built. With the second model, the room was maintained a temperature of 28°C in summer which could be considered satisfactory for the composite climate.

(a)



(b)

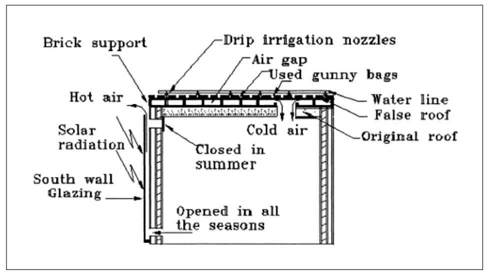


Figure 2. Schematic diagram of two passive models for summer operation in a composite climate of India. (Source: Raman, Mande & Kishore, 2001, pp. 319-329)

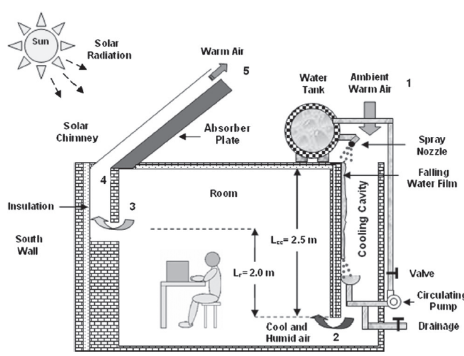


Figure 3. Schematic diagram of solar chimney and cooling cavity. (Source: Maerefat & Haghighi, 2010)

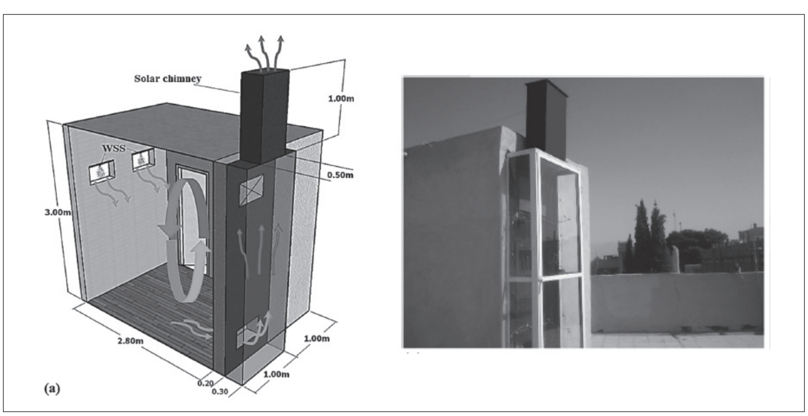


Figure 4. The Trombe wall integrated with the solar chimney and the water spraying system (WSS). (Source: Mehran, Vali, Ali & Ahmadreza, 2015)

The theoretical research on the combination of evaporative cooling together with the solar chimney was studied by Maerefat and Haghighi (2010). Figure 3 shows the schematic diagram of the design in this work. The cooling cavity utilized the water film was added to the room. The cooling cavity was expected to absorb heat from the ambient air before entering the room to provide a comfortable temperature. For the ambient air of 34-40°C and relative humidity of 30-80%, this system was shown to reduce air temperature in the room to 25.5-36°C with the increase in relative humidity to 82.9-93.3%. The calculated results of relative humidity were high but the system can reduce the air temperature substantially.

The direct evaporative cooling has been widely used in hot-dry climate where relative humidity is quite low. The relative humidity during the daytime was 8-19% at ambient temperature about 35°C. Under this climatic condition the thermal efficiency of utilizing of an experiment on evaporative cooling within the room ventilated by a solar chimney was as high as 80% (Mehran et al., 2015). With the new configuration, the Trombe wall can be used together with the solar chimney (Figure 4). The solar chimney (the black box on the top of the channel) can be removed from the system for heating mode. The external wall made of glazing material in three direction allowed high solar intensity all over the year. The water spraying systems (WSS) that produced tiny droplets of water were installed at the two windows. The droplets size of 30 µm with the flow rated of 10 l/hr. were recommended. With the water spraying system, the temperature reduced by 8 °C and the relative humidity increased by 17%.

The performance of a solar chimney applied with damped sheets to reduce the glazing surface temperature was investigated (Touma, Ghali, Ghaddar & Ismail, 2016, pp. 169-179). The proposed system shown in Figure 5a composed of three main components; evaporative cooler, glazing section and solar chimney located consecutively above each other. As air being driven upward by the solar chimney, it passed through the evaporative cooler and the glazing section. The evaporative cooler consisted of a vertical rectangular channel with four water absorbing sheets installed along its height. A small reservoir and a pump were also provided at the bottom of the channel to ensure continuous water supply to these sheets. Effect of radiation on the evaporative cooler were assumed neglected from the outer surface of the channel. There were two glazing sections in this system, the outer glass and the room's window. Both glazing sections were closed to let the air flow only in the vertical direction.

The psychrometric process of the air in the proposed system is shown in Figure 5b. Outdoor air at state 1 entered the damped space between sheets where it was humidified and reduced temperature via mass and heat transfer with the water sheets until it reached state 2. Air passed to glazing section where it extract heat and its temperature rose to state 3. At state 4 air extracted more heat before getting exhausted out of the solar chimney. The experimental results showed reduction in space load 19.8%. The window temperature without the operation of the solar chimney was 28°C. With the solar chimney operation, the cooled air passed the window, window temperature was 26°C. This system was also numerical simulated and the model was validated with the experimental results. Prediction results showed that this system was inappropriate to apply in the location with humid climate.

Figure 6 shows schematic diagram of the adsorption cooling integrated with the solar chimney. In this study (Jafari & Poshtiri, 2017, pp. 662-682) the two-bed silica gel-water adsorption chiller was employed and chilled water in the cooling plate was used to cool fresh air in the cooling cavity. The mathematical model of the solar

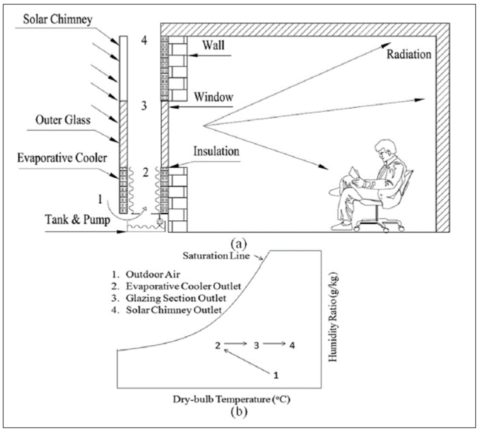


Figure 5. Schematic of a) the system of solar chimney and evaporative cooling applied on the window's outer surface and b) air property changes on the psychrometric chart. (Source: Touma, Ghali, Ghaddar & Ismail, 2016, pp.169-179)

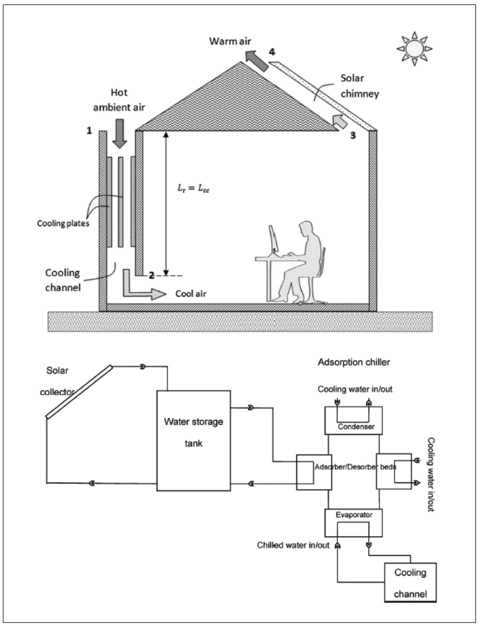


Figure 6. a) Schematic representing the room and b) schematic representing the solar cooling system. (Source: Jafari & Poshtiri, 2017, pp. 662-682)

cooling system was developed together with the solar chimney. The condensation of air moisture through was also modeled to analyze the effect of moisture on the whole system performance. Two climatic data in two cities, Tehran with low ambient humidity and Bandar Abbas with high ambient humidity, were involved in the analysis.

The results showed that room air temperature remained within the comfort limits. Temperature in the room was 20-32°C for the cooling demand of 4,000-8,000 W in both climatic conditions. The air change rate did not change much because of the consistent in the total ventilation draft. The total ventilation draft consisted of the difference of buoyancy forces between point 3 and 4 (solar chimney draft), between point 2 and 3 (room draft), and between point 1 and 2 (cooling channel draft). It was found that the primary draft comes from the buoyancy force in the cooling channel. Hence, the solar chimney can be omitted and be replaced by a window. According to the analysis, the high ambient relative humidity and the condensation in the channel reduced the temperature in the channel and reduces the channel's draft, and as a result, the total draft decreased.

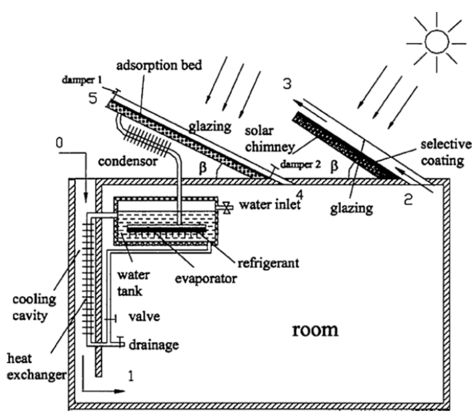


Figure 7. Schematic of solar house with solar chimney and adsorption cooling cavity. (Source: Dai, Sumathy, Wang & Li, 2003, pp. 65-75)

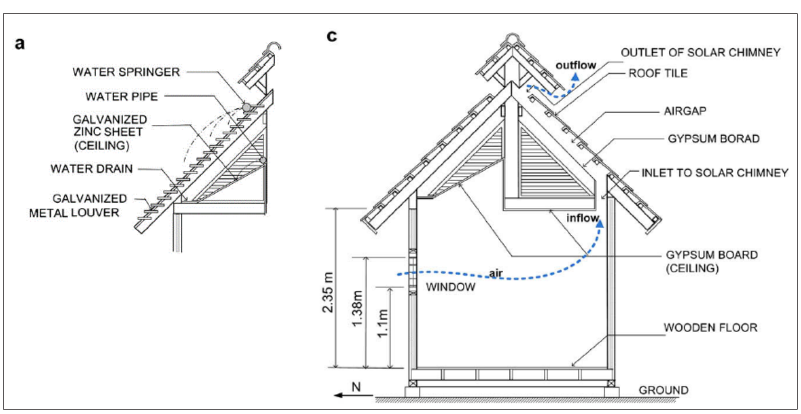


Figure 8. Water spraying on the North roof and the detached building with a roof solar chimney on the South roof. (Source: Chungloo & Limmeechokchai, 2007, pp. 3341-3351)

2.2. Indirect evaporative cooling

The indirect evaporative cooling found in the combination with the solar chimney were the adsorption cooling system and water spraying on the building's envelope surfaces. The adsorption cooling system supplied and circulated the refrigerant to the heat exchanger in the cooling cavity (Dai, Sumathy, Wang & Li, 2003, pp. 65-75). As shown in Figure 7, the fresh air in cavity was cooled by the heat exchanger before entering the room and flowed into the solar chimney on the roof. The solar house with a 2.5 m^2 solar chimney was able to crate air flow rate of more than 0.042 kg/s for the house. Furthermore, the ventilation rate at night was also increased by 20% with the solar adsorption cooling cavity. With this method, the room was cooled without any change in humidity.

The thermal performance of the passive cooling system using solar chimney and the water spraying system was experimentally studied in the hot and humid climate of Thailand (Chungloo & Limmeechokchai, 2007, pp. 3341-3351). Figure 8 shows the system that the water spraying system and the solar chimney were located on the North roof and the South roof, respectively. The results were collected in two rooms, one with the solar chimney and the water spraying system and the reference room equipped with the solar chimney. The results showed that the combined system decreased room temperature by 1-3.2°C comparing to the reference room and 6°C comparing to the ambient room.

Table 1 indicates the experimental and numerical results obtained in the previous studies. The ambient temperature in the hot-humid climate (Chungloo & Limmeechokchai, 2007, pp. 3341-3351) was similar to those in the hot-dry climate, ranging from 26-42 °C during the daytime. In the hot-dry climate, the room temperature was reduced obviously comparing to the ambient air after applying the direct evaporative cooling. The lowest

Table 1. Air temperature, humidity air velocity inside the room and the solar chimney.

References	Study method	Air temperature (°C)			Relative Humidity (%)		Average air velocity (m/s)	Flow rate
		Ambient	Room	Solar chimney	Ambient	Room	Room	
Raman, Sanjay, Mande & Kishore, 2016	Experiment							
(gunny bag)	26-42	29-31	N/A	20-99	39-90	N/A		
Dai, Sumathy, Wang & Li, 2003	Numerical model (indirect Adsorption)	29-37	26-34	41-65	N/A	N/A	N/A	0.042 kg/s (Max)
Chungloo &Limmeechokchai, 2007	Experiment (Indirect evaporative)	29.5-36.3	27.9-33.7	29.1-36.2	46.6-73.5	46.6-73.5	N/A	1.13-2.26 ACH
Maerefat & Haghighi, 2010	Numerical model (cooling cavity)	34-40	25.5-36		30-70	82.9-93.3	N/A	2.4-4.3 ACH
Mehran, Kalantar, Ali & Ahmadreza, 2015	Experiment (water spray)	30.1-38.5	29.7-35.6	40.5-46.0	8-19	10.7-34.3	0.14-0.28	0.023-0.052 kg/s
Touma, Ghali, Ghaddar & Ismail, 2016	Experiment (evaporative cooling)	28 30	N/A	28.3 31.9	35 30	N/A	N/A	N/A
Jafari & Poshtiri, 2017	Numerical model (adsorption cooling w/o condensation)	32-38	17-30	N/A	20-60 (Tehran)	20-60 (Tehran) 100 (Bandar Abbas)	N/A	10.9-12.6 ACH

room temperature was 17-30 °C in the application of adsorption cooling together with the solar chimney (Jafari & Poshtiri, 2017, pp. 662-682). The air temperature in the vertical solar chimney were higher than that in the room by 6-1 °C (Mehran, Kalantar, Ali & Ahmadreza, 2015, pp. 45-57). This indicated a high draft force in the system. The evaporative system worked so well due to the low relative humidity in the ambient. The increase in relative humidity in the room varied from 70-90% (Maerefat & Haghighi, 2010, pp. 2040-2052) in the numerical study and 10-34% (Mehran, Kalantar, Ali & Ahmadreza, 2015, pp. 45-57) in the field experiment. There were a few report on the air velocity in the room. The air change rate per hours were lowest in the indirect evaporative cooling in hot-humid climate and highest in the cooling by solar adsorption in hot-dry climate.

3. The water vapor transport model

3.1. Mass diffusion

The rate of mass diffusion ($\dot{m}_{diff}$) of a chemical species a in a stationary medium in the direction x is proportional to the concentration gradient *dC/dx* in that direction and is expressed by Fick's law of diffusion by (Cengel, 2004) as follows,

$$\dot{m}_{diff} = -D_{ab}\frac{dC_A}{dx} \qquad \text{(Eq. 1)}$$

where D_{ab} is the diffusion coefficient (or mass diffusivity) of the species in the mixture and C_a is the concentration of the species in the mixture at that location. Fick's law states that the rate of diffusion of a chemical species at a location in a gas mixture is proportional to the concentration gradient of that species at that location. Eq. (1) can be expressed as

Mass flux = Constant of proportionality x Concentration gradient

The concentration of a species in a gas mixture can be defined in several ways such as density, mass fraction, and molar concentration. The common way to express the concentration of a species. In the mass basis, concentration is expressed in terms of density (ρ, kg/m^3), which is the mass per unit volume. Consider a small volume V at a location within the mixture, the density of a species (subscript i) and of the mixture (no subscript) at that location are given by

Partial density of species i : $\rho_i = m_i/V$ (Eq. 2)

Total density of mixture : $\rho = m/V = \sum m_i/V = \sum \rho I$ (Eq. 3)

Mass fraction of species i : $w_i = \frac{m_i}{m} = \frac{m_i/V}{m/V} = \frac{\rho_i}{\rho}$ (Eq. 4)

Thus, Ficks's law for diffusion of a species a in a stationary binary mixture of species a and b in a specified direction x in mass basis is given by

$$j_{diff,a} = \frac{\dot{m}_{diff,a}}{A} = -\rho D_{ab} \frac{d(\rho_a/\rho)}{dx} = -\rho D_{ab} \frac{dw_a}{dx} \quad \text{(Eq. 5)}$$

Here, $j_{diff,\,a}$ is the diffusive mass flux of species a. It is the mass transfer by diffusion per unit time and per unit area normal to the direction of mass transfer, in kg/s.m^2. The mass flux of a species at a location is proportional to the density of the mixture at that location. Note that $\rho = \rho_a + \rho_b$ is the density of the binary mixture and they may vary throughout mixture. The binary diffusion coefficient of dilute gas mixture at 1 atm of air and water vapor at 298 K is 2.5 x 10^{-5} m^2/s (Cengel, 2004). The empirical formulas have been developed for the diffusion coefficient $D_{H2O\text{-}air}$. Marrero and Mason (1972) proposed this popular formula (Marrero & Mason, 1972, pp. 3-118):

$$D_{H_2O\text{-}Air} = 1.87 \times 10^{-10} \frac{T^{2.072}}{P} \quad (\text{m}^2/\text{s}),\ 280\ \text{K} < T < 450\ \text{K} \quad \text{(Eq. 6)}$$

3.2 Mass convection

Mass convection is the transfer of mass between a surface and a moving fluid due to both mass diffusion and bulk fluid motion. Fluid motion enhances heat transfer considerably by removing the heated fluid near the surface and replacing it by the cooler fluid. Likewise, fluid motion enhances mass transfer by removing the high-concentration fluid near the surface and replacing it by the lower-concentration fluid further away. Without the bulk fluid motion, mass convection reduces to mass diffusion. The analogy between heat and mass convection holds for both forced and natural convection, laminar and turbulent flow, and internal and external flow. The rate of mass convection can be expressed as (Cengel, 2004)

$$\dot{m} = h_m A\left(\rho_{A,s} - \rho_{A,\infty}\right) = h_m \rho A\left(w_{A,s} - w_{A,\infty}\right) \quad \text{(Eq. 7)}$$

Where h_m is the average mass transfer coefficient (m/s), A is the surface area, $\rho_{A,s}$ - ρ_{A}, ∞ is the mas concentration difference of species A across the concentration boundary layer, and ρ is the average density of the fluid in the boundary layer. Assuming the Lewis number of unity for air-vapor mixture, hm is determined from (Touma, Ghali, Ghaddar & Ismail, 2016, pp. 169-179)

$$h_m = \frac{h_c}{\rho_{air} \times c_{p,air}} \quad \text{(Eq. 8)}$$

Where h_c is the convection heat transfer coefficient, the ρ_{air} and $c_{p,\,air}$ are the density and specific heat of air at mean conditions. The value of h_c is calculated from (Cengel, 2004):

$$Nu = \frac{h_c L_c}{k_{air}} \quad \text{(Eq. 9)}$$

Where Nu is the Nusselt number, L_c is the characteristic length and k_{air} is the thermal conductivity of air. Since flow in the solar chimney are dominated by free natural convection, Nusselt number is found by the empirical correlations for free convective flow between parallel plates subjected to constant heat flux on one side and adiabatic on the other side.

3.3 Species transport in the Computational Fluid Dynamics (CFD)

The CFD program have been used to analyze the heat transfer and fluid flow in the solar chimney and the room. The air in the solar chimney system was assumed as an ideal gas (Lei, Zhang, Wang & Wang, 2016, pp. 653-661; Gan, 2010, pp. 1290-1300; Zamora & Kaiser, 2010, pp. 2080-2088; Khanal & Lei, 2015, pp. 217-226). Recently, the research work conducted by author found that humidified air would be a moist air which composed of dry air and moisture. The analysis of moist air in the solar chimney was successfully found representing moist air in the hot and humid climate in the previous study (Sudprasert, Chinsorranant & Rattanadecho, 2016, pp. 645-656). Therefore, this study reviewed the mathematical modeling of the species transport found in the ANSYS Fluent program. For all flows, the ANSYS Fluent program was used to solve the conservation equations for mass and momentum. For flows involving a mixture of species, the species conservation equation was solved in the CFD program. To solve conservation equations for species, the ANSYS Fluent software predicts the local mass fraction of each species, Y_i, through solution of a convection-diffusion equation for the i^{th} species. This conservation equation takes the following form (Ansys, 2013):

$$\frac{\partial}{\partial t}\left(\rho Y_i\right)+\nabla\cdot(\rho u_i Y_i)=-\nabla\cdot J_i \qquad \text{(Eq. 10)}$$

Y_i Local mass fraction of each species
u_i Mean velocity component corresponding to i direction (m/s)
Ji Mass diffusion (kg/s.m^2)
∇ in the three-dimensional Cartesian coordinate system, the gradient is given by:

$$\nabla f=\frac{df}{dx}i+\frac{df}{dy}j+\frac{df}{dz}k \qquad \text{(Eq. 11)}$$

In analysis of water vapor diffusion into air, there are two species in the CFD model: water vapor (species 1) and air (species 2). In turbulent flow, ANSYS Fluent computes the mass diffusion in the following form:

$$J_i=-\left(\rho D_{i,m}+\frac{\mu_t}{Sc_t}\right)\nabla Y_i-D_{i,T}\frac{\nabla T}{T} \qquad \text{(Eq. 12)}$$

$D_{i,m}$ Mass diffusion coefficient for species i in the mixture (m^2/s)
$D_{i,T}$ Thermal diffusion coefficient for species i in the mixture (m^2/s)
Sc_t Turbulent Schmidt number
μ Laminar dynamic viscosity (kg/m•s)

4. Conclusions

This paper reviewed the application of evaporative cooling in the solar chimney. In the hot-dry climate, with the ambient relative humidity in the range of 19-35%, the direct evaporative cooling by water spraying and water film were found possible. The decrease of air temperature was found as high as 6 °C and 15°C in field measurement and by theoretical analysis, respectively. There was a discrepancy between the theoretical and experimental result about 50%. According to psychometric, this corresponded to the increase of 6 to 7 grams of water vapor in the air. The indirect evaporative cooling reduced air temperature by 3 °C in hot-dry and hot-humid climate in summer. The trend of utilizing direct evaporative cooling together with the solar chimney seemed to be limited in the hot dry climate. In the hot and humid climate, the evaporative cooling was possible during summer. During daytime in summer of Thailand, the relative humidity was around 51%, indicating an opportunity in apply direct evaporative cooling.

There were no report on effect of high water content on the air flow rate from the field experiments. However, numerical study showed that increase of water vapor in the air reduced the flow rate because of the heavier air of higher heat capacity. The mathematical based on mass diffusion and convection have already separated the water content analysis from the dry air before the mixing them in the results as moist air. The knowledge gap about the effect of increasing water vapor on the moist air flow is needed to be filled by new research.

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