The Field Investigation of Dimensionless Convection Heat Transfer Coefficient in the Inclined Roof Solar Chimney
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Abstract

The objectives of this paper are to study the free convection in the air gap of a 45-degree inclined roof solar chimney and to experimentally determine the correlation of Nusselt number (*Nu*). The experiment was carried out in an open-ended air gap between the corrugated roof tile and the gypsum board attached to a detached building with the inner width and length of 18 and 160 cm. located outdoor under the hot and humid climate. The surface temperatures of the corrugated roof tile are between 35-45°C during the daytime of May and June, exposed to the solar intensity of 200-1,000 W/m^2. The data reduction using linear regression analysis yields linear relationships of mean bulk temperature, temperature difference of air at inflow and outflow, heat transfer rate and mass flow rate of the solar chimney against the temperature difference of hot roof surface and the mean bulk temperature (T_h–T_b). Employing the derived linear relationships, the correlation between the Nusselt number, Nu_s, Rayleigh number, Ra_s, and the aspect ratio (air gap/length) are derived for $3^{\circ}C \leq T_h - T_b \leq 9^{\circ}C$ as $Nu_s = 1.444 \cdot [(S/L)\, Ra_s \sin 45^{\circ}]^{0.249}$. It is the correlation that could be used for determination of mean convection heat transfer coefficient of the roof solar chimney with similar geometry applied in the hot and humid climate, provided that it is in the same range of *Ra* value and the same range of *Ra (S/L)* value.

บทคัดย่อ

บทความนี้แสดงผลการศึกษาการพาความร้อนแบบอิสระในช่องว่างอากาศกว้าง 18 เซนติเมตร ยาว 160 เซนติเมตร และเอียง 45 องศา ภายใต้สภาวะภูมิอากาศร้อนชื้น และนำเสนอความสัมพันธ์ของเลขนัสเซลต์ที่ได้จากการทดลองภาคสนาม การทดลองกระทำในช่องว่างอากาศปลายเปิดสองด้านที่ตั้งอยู่ระหว่างกระเบื้องหลังคาลอนคู่และแผ่นฝ้าเพดานยิปซั่มของห้องทดลองกลางแจ้ง ผลการทดลองแสดงว่าอุณหภูมิผิวหลังคาด้านติดกับช่องว่างอากาศมีค่าอยู่ที่ 35-45°C เมื่อได้รับรังสีอาทิตย์ที่มีค่าอยู่ระหว่าง 200-1,000 วัตต์ต่อตารางเมตร การวิเคราะห์ด้วยสมการถดถอยพบความสัมพันธ์เชิงเส้นสามความสัมพันธ์ คือ ความสัมพันธ์เชิงเส้นระหว่างค่าความต่างอุณหภูมิผิวกับ

อุณหภูมิอากาศเฉลี่ย (mean bulk temperature, $T_h – T_b$) กับค่าความต่างของอุณหภูมิอากาศที่ทางเข้าและออกระหว่างค่าความต่างอุณหภูมิผิวกับอุณหภูมิอากาศเฉลี่ยกับอัตราการถ่ายเทความร้อน และระหว่างค่าความต่างอุณหภูมิผิวกับอุณหภูมิเฉลี่ยกับอัตราการไหลของอากาศผ่านปล่องรังสีอาทิตย์ ความสัมพันธ์เชิงเส้นดังกล่าวนำมาคำนวณหาความสัมพันธ์ระหว่างเลขนัสเซลต์ (Nusselt number, Nu) กับเลขเรย์ลี (Rayleigh number, Ra) และอัตราส่วนช่องว่างอากาศกับความยาวปล่อง (*S/L*) ในช่วงค่าความต่างอุณหภูมิผิวกับอุณหภูมิอากาศเฉลี่ยเท่ากับ 3°C-9°C ได้ว่า $Nu_s = 1.444 \cdot [(S/L)\ Ra_s \sin 45^{\circ}]^{0.249}$ โดยความสัมพันธ์ของ Nu ที่ได้รับคือความสัมพันธ์ไร้มิติของสัมประสิทธิ์การพาความร้อน (dimensionless convection heat transfer coefficient) สำหรับปล่องรังสีอาทิตย์ของงานวิจัยนี้และสามารถนำไปประยุกต์ใช้กับปล่องรังสีอาทิตย์อื่น ๆ ที่มีรูปแบบใกล้เคียงกัน

คำสำคัญ (Keywords)

Free Convection Heat Transfer (การพาความร้อนแบบอิสระ)
Inclined Roof Solar Chimney (ปล่องรังสีอาทิตย์แบบเอียง)
Data Correlation (สหสัมพันธ์ข้อมูล)
Convection Heat Transfer Coefficient (สัมประสิทธิ์การพาความร้อน)
Dimensionless (ไร้มิติ)

Nomenclatures			
A	Area of the hot surface (m^2)	S	The space between the roof tile and the gypsum board (m)
$A_{channel}$	Area of the opening of the solar chimney (m^2)	T_b	Mean bulk temperature (°C)
C_D	Coefficient of discharge	T_h	Temperature of the hot surface = ($T_{roof,\ outlet}$ + $T_{roof,\ inlet}$)/2 (°C)
c_p	Specific heat (J/kg)	T_i	Temperature of air at the inflow to the solar chimney (°C)
g	Gravitational acceleration (m/s^2)	T_o	Temperature of air at the outflow of the solar chimney (°C)
$\overline{h}$	Mean heat transfer coefficient (W/m^2K)		
k	Thermal conductivity (W/mK)		
L	Length of solar chimney (m)		
$\dot{m}$	Mass flow rate (kg/s)		
Nu_s	Nusselt number = $\frac{h \cdot S}{k}$	**Greek symbols**	
Pr	Prandtl number	β	Coefficient of thermal expansion (K^{-1})
Q	Heat transfer rate (W/m^2)	ρ	Density (kg/m^3)
Ra_s	Rayleigh number	θ	Tilt angle of the solar chimney
Re_s	Reynolds' number = $\frac{V \cdot s}{\nu}$	ν	Kinematic viscosity of the fluid (m^2/s)

1. Introduction

The inclined solar chimney is a distinguish device applied for passive ventilation in the hot and humid climate (Chenvidyakarn, 2007). According to the passive cooling application by using a solar chimney system, determination of heat transfer coefficient (*h*) between the hot plate and the hot air in the channel and Nusselt number (*Nu*) are important in the investigation of free convection, mathematical simulation and application of the system. The determination of the correlation between Nusselt number (*Nu*) and Rayleigh number (*Ra*) in the vertical plates and inclined channels involving of heated plates has been carried out in many research works. The scaling analysis (Ostrach, 1953) of the fluid with Prandtl number (*Pr*), $Pr<<1$ showed that *Nu* is scaled by $(Ra\ Pr)^{0.25}$. Azevedo and Sparrow (1985) found the correlation for the symmetric isothermal plates and isothermal-insulated plates by carrying out experiments on the inclined channels in the water. Their experiments of inclined channel showed the correlation of $Nu_s = 0.645\ [Ra_s(S/L)\cos\theta]^{0.25}$ (Azevedo & Sparrow, 1985). Hirunlabh et al. (2001) showed that *Nu* and air flow rate in the application of the inclined solar chimney can be computed by using the correlation derived in Gebhart (1971). The analysis of the data on the experiment in the laboratory (Khedari et al., 2002) showed that the inclined parallel plate channel with temperature varying from 40-70°C yielded the correlation of $Nu_s = 1.227\ [(S/L)\ Ra_s \sin 30°]^{0.2916}$. The derived heat transfer coefficients are between 6.76 and 10.26 W/m^2K (Khedari et al., 2002).

However, the free convection in the open-ended channel such as the application of solar chimney in the outdoor field has been rarely investigated. Frequently, the correlations derived from the laboratory research are used as the estimation of heat transfer coefficient. The objective of this paper is to determine the correlation of Nu_s for the inclined solar chimney in the outdoor field, where the temperature differences and Ra_s values are different from the previous studies. By conducting the experiments on one of the four channels of solar chimney attached to a testing building located outdoor, the new correlation between the Nu_s and the Ra_s is proposed. Also, this study shows the effect of variation of solar intensity and the effect of heat loss from the inclined channel on the range of *Ra* values. Taking into account those ambient conditions and the result of particular range of Ra_s value, the correlation between the Nu_s and Ra_s are revised. The comparison of derived heat transfer coefficients with the coefficients derived from Azevedo and Sparrow (1985), Gebart (1971), and Khedari et al. (2002) are also discussed.

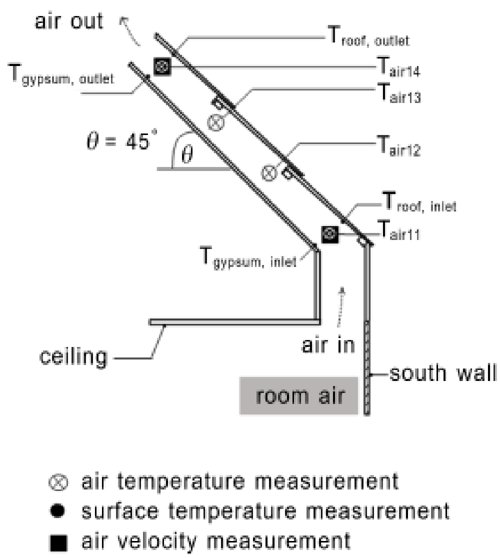

Figure 1. Schematic representation of the inclined roof solar chimney.

2. Experimental Set-up and Methodology

The experiments were carried out in one of the four channels of the solar chimney installed above the room of a testing building. The corrugated roof tiles are fixed over the 45-degree inclined wooden structure of the roof, facing the south direction exposing the external surface to outdoor environment and heated up by the sun during daytime. The gypsum board covers the lower part of inclined wooden structure and external surface faces the air in the attic above the ceiling (Figure 1). The total width and length and average channel space of the solar chimney are 960 mm, 1660 mm, and 185 mm, respectively, aspect ratio (*S/L*) of 0.115. The positions of temperature and velocity measurement are shown in Figure 2. There are 16 type-k thermocouples used to measure temperature, 8 for measuring air temperature of the channel, 4 for measuring surface temperature of roof tiles and gypsum boards, 3 for measuring air in the room, and 1 for measuring temperature of the outdoor air. Two hot-bulb probes are placed to measure air velocity at the inlet and at the outlet of the channel which are opened to the room air and outdoor, respectively. In addition, the outdoor conditions such as solar intensity and wind velocity are recorded by a pyranometer Kipp & Zonen-CM11 and Yong

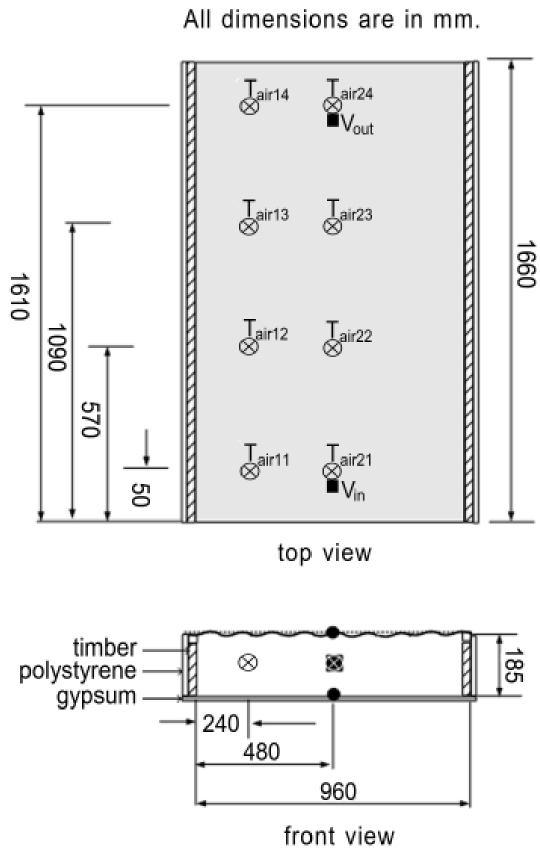

Figure 2. Positions of measuring temperature and velocity of air.

wind monitor, respectively. To record the data simultaneously for every 2 minutes during the day, all thermocouples and devices are connected to the Yokogawa-DR130 data logger. The experiments are carried out on 5 selected days in May and June.

3. Experimental Results

3.1 Alteration of Temperature of Internal Surface of Roof Tile (T_h) and Temperature of Inflow (T_i) and Outflow (T_o) of the Solar Chimney with Solar Intensity

According to the values of solar intensity (W/m^2) of 5 days in May and June, the experimental results of temperatures of the internal surface of roof tile (T_h), temperature at the outflow (T_o) and at the inflow of the solar chimney (T_i) are shown in Figure 3. The values of T_h and T_i increase from 29 and 31°C in the morning to 38 and 32°C in the afternoon, according to the values of solar intensity of 100 and1000 W/m^2, respectively. After the peak value of solar intensity of 1000 W/m^2 during 12.30-14.00, the solar intensity decrease steadily as well as the temperatures of internal surface of roof tile, T_h. However, the increasing of T_i and T_o to 36°C and the decreasing of temperature difference (T_o–T_i) imply that there is less air flow rate passing through the solar chimney in the afternoon than in the morning. This is the effect of high ambient and room temperatures in the afternoon in the hot and humid climate (Chungloo & Limmeechokchai, 2007).

3.2 The Effect of the Clouds on Temperature Differences and Utilization of the Solar Chimney

The effect of the clouds obstructing the sun radiation on the surface and air temperatures of the solar chimney is also shown in Figure 3 by the scattering of temperatures, T_h, T_i and T_o, in the range of solar radiation between 200-400 W/m^2.

However, the temperature differences of (T_h–T_b) and (T_o–T_i) show linear relationship with the values of solar intensity greater than 450 W/m^2 (Figure 4). According to data collected during the clear and sunny sky in Figure 4, the solar induced ventilation starts when the temperature differences (T_o–T_i) are greater than 0°C at the global solar intensity of 500 W/m^2 and (T_h–T_b) ≈ 2.0. The maximum values of (T_h–T_b) and (T_o–T_i) are 8 and 5°C, respectively for the solar intensity of 950 W/m^2. In the early morning and evening with solar intensity less than 200 W/m^2, the values of T_h–T_b are less than 2°C and air is induced into the room through the channel due to T_o<T_i. It is shown that the solar chimney can be used for enhancing cool air induced into the room during the early morning and evening and expelling the hot air from the room to ambient during daytime. In addition, the determination of correlation in this study covers the values of temperature difference, T_h–T_b from 0 to 9°C when the global solar intensity is greater than 450 W/m^2.

4. The Data Analysis and Comparison with Previous Correlations

4.1 Mathematical Models

The Nu_s is evaluated by

$$Nu_s = \frac{\bar{h} \cdot S}{k}, \tag{1}$$

where
$$\bar{h} = \frac{Q}{A \cdot (T_h - T_b)} \tag{2}$$

As the heat loss from the roof tiles and gypsum board and radiative exchange are neglected and Q is the heat transfer rate of the roof tile computed from

$$Q = \dot{m} \cdot c_p (T_o - T_i) \tag{3}$$

where
$$\dot{m} = \rho \cdot A_{channel} \cdot V$$

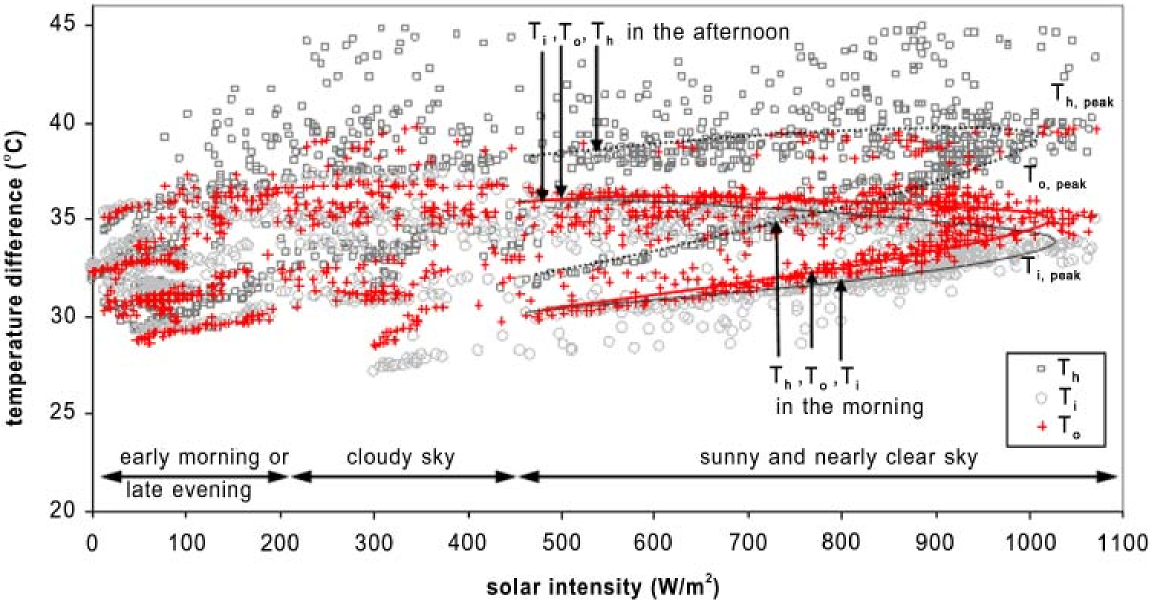

Figure 3. Experimental results of surface temperature *(T_h)*, inflow *(T_o)* and outflow *(T_i)* air temperature of the solar chimney plotted against solar intensity (W/m^2).

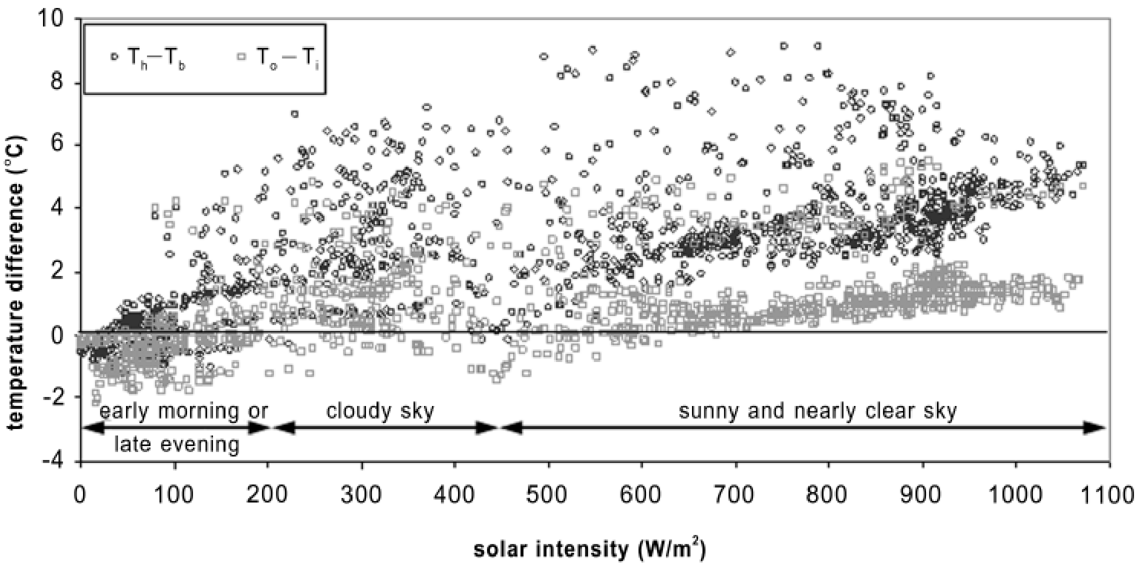

Figure 4. Experimental results of temperature differences, T_h–T_b and T_o–T_i , vs. solar intensity.

The Nu_s results will be correlated by the dimensionless group Ra_s, theoretically evaluated by

$$Ra_s = [g\beta\,(T_h - T_b)\,S^3/\nu^2] \cdot Pr \quad (4)$$

All thermophysical properties of air are evaluated at the bulk temperature of air, T_b. By using the Trapezoidal rule reported in Khedari et al. (2002), T_b in this study can be estimated from

$$T_{b1} = (T_{air11}+3T_{air12}+3T_{air13}+T_{air14})/8, \quad (5a)$$

$$T_{b2} = (T_{air21}+3T_{air22}+3T_{air23}+T_{air24})/8 \quad (5b)$$

and

$$T_b = (T_{b1}+T_{b2})/2 \quad (6)$$

Temperature of air at the inlet T_i is computed from average values of temperature of room air near the ceiling. Temperature of air at the outlet T_o and temperature of internal surface of roof tile, T_h are from experimental results. The mass flow rate of air in the solar chimney can be estimated by

$$V = C_D \cdot \rho \cdot \sqrt{g \cdot L \cdot sin45^\circ \cdot \frac{(T_o - T_i)}{T_i}} \quad (7)$$

where the value of C_D in this study is 0.4 (Chungloo & Limmeechokchai, 2007).

4.2 Data Reduction

The purpose of data reduction is to carrying out the linear relationships between $(T_h – T_b)$ and other variables such as heat transfer rate per area *(Q/A)*, mean bulk temperature (T_b), temperature difference at the inflow and outflow, $(T_o – T_i)$ and mass flow rate of air $(\dot{m})$ before determination of values of Nu_s and Ra_s.

For the increase of values of $T_h – T_b$ of 0 to 9°C, the increase of mean bulk temperature (T_b) during the low inflow temperature (T_i) is faster than during high inflow temperature, producing two different linear relationships. However, the two difference linear relationships between $T_h – T_b$ and T_b are averaged as shown in Figure 5a. The linear relationships between $T_h – T_b$ and $T_o – T_i$, *Q/A* and $\dot{m}$ are shown in Figure 5b and 5c, respectively.

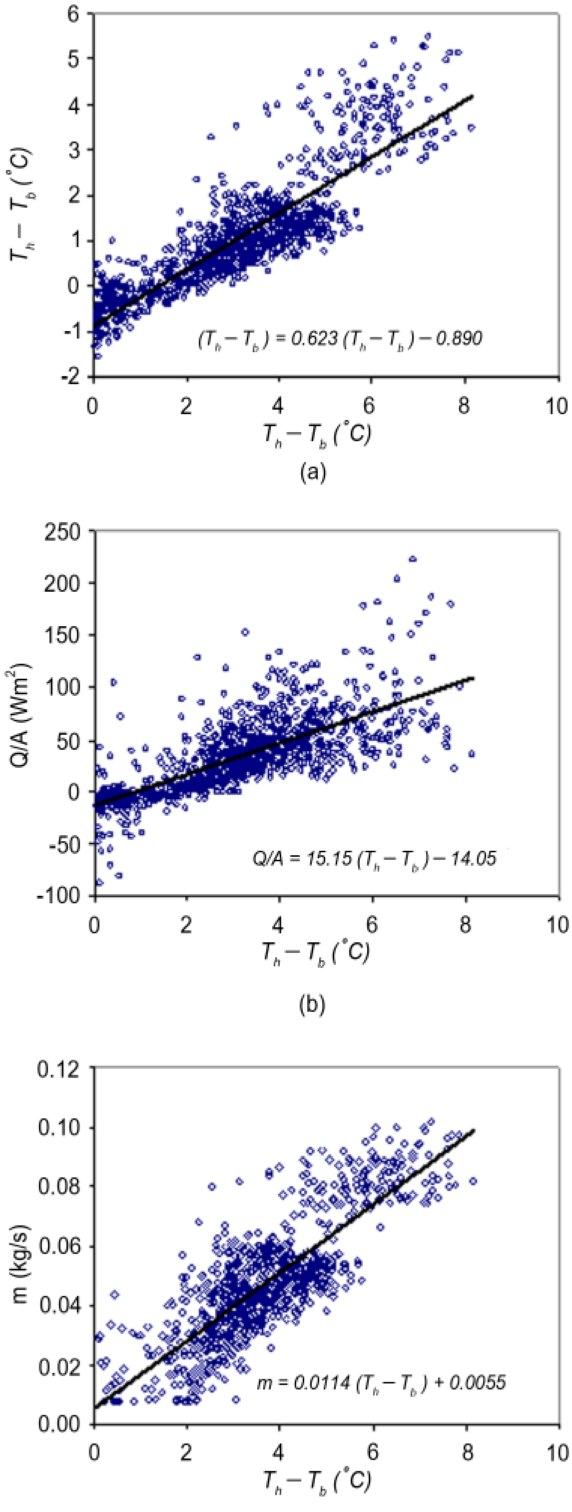

Figure 5. Linear relationships between $T_h – T_b$ and $T_o – T_i$, Q/A and $\dot{m}$.

The calculated values of T_o–T_i, *Q/A* and by using the derived linear equations and the calculated values of velocity *(V)* and convective coefficient, *(h)* by using Equation 2 and Equation 7 are summarized in Table 1. The related dimensionless groups Nu_s, Re_s and Ra_s are also computed and shown in Table 1.

The Nusselt number, Nu_s, is the non-dimensional expression of heat transfer coefficient, $\bar{h}$. The correlations between Nusselt number and Rayleigh number, angle of channel and aspect ratio (*S/L*) are typically in the form

$$Nu_s = a \cdot [(S/L) \cdot Ra_s \cdot sin\theta]^b \quad (8)$$

Based on the value of Ra_s and Nu_s in Table 1, the constants *a* and *b* are obtained by means of least square analysis to the logarithms of Equation 9 as followed:

$$Nu_s = \frac{\bar{h}S}{k}$$

$$Nu_s = 1.444 \cdot [(S/L) \cdot Ra_s \cdot sin45^\circ]^{0.249} \quad (9)$$

For Equation 9, the range of Ra_s and T_h–T_b are $1.543 \times 10^7 < Ra_s < 4.193 \times 10^7$ and $3.00^\circ C \leq T_h - T_b \leq 9.00^\circ C$. The computational results of Equation 9 are graphically shown as solid lines in Figure 6.

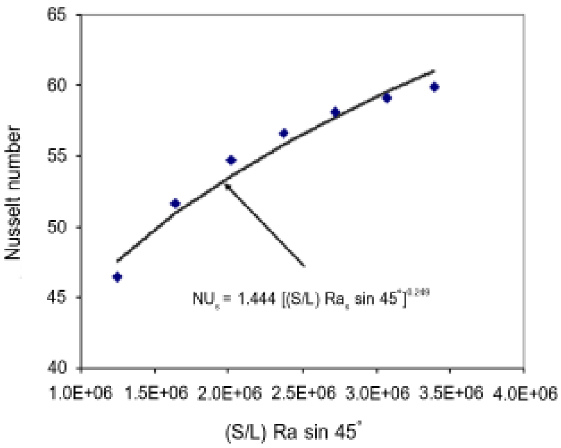

Figure 6. Nusselt number vs. *(S/L)* · Ra_s · *sin 45°*.

4.3 Comparison with Previous Correlations

The comparison of Ra_s values in Table 2 shows that the range of Ra_s value in this study is higher than that found in the other studies. Since the Ra_s value is the function of T_h–T_b, this means the higher temperature differences occurs in this study than that occurs in the previous studies. The comparison of Nu_s (this study) with Nu_s (Azevedo & Sparrow, 1985) and Nu_s (Gebhart, 1971) at the same value of channel aspect ratio (S/L) and tilt angle (θ) shows that the present study provides higher value of Nu_s.

For the same value of (*S/L*) but different tilt angle, the value of Nu_s (this study) is higher than the value of Nu_s (Khedari et al., 2002). Since the similar exponential functions are used, it is concluded that increasing the tilt angle by 15 degree changes the correlation, increases the Ra_s values, increases the Nu_s values and hence increases the value of heat transfer coefficient (*h*).

It is also shown in the Table 2 the significant impact of Ra_s value on the Nu_s value in each correlation. Since each of the correlations exists in the specific range of temperature difference (T_h–T_b), there is no direct comparison among these correlations. The proposed correlation here, therefore, increases the value of heat transfer coefficient (*h*) of the free convection heat transfer in the extended range of *Ra* value.

5. Conclusions

Under the condition of hot and humid climate, the free convection was studied in a hot air channel of the 45-degree inclined roof solar chimney. The investigation includes collecting data of surface and air temperatures in the channel, analyzing and reducing experimental data and determining the correlation between non-dimensional groups, i.e. Nu_s, Ra_s, the aspect ratio (gap/length) and the angle

Table 1. Summary of the experimental and calculated data.

Quantity	**Unit**	***S/L* = 0.1145**									
Variables correlated with $(T_h - T_b)$											
$T_h - T_b$	°C	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00
T_b	°C	32.70	33.10	33.50	33.90	34.30	34.70	35.10	35.50	35.90	36.40
$T_o - T_i$	°C	-0.89	-0.27	0.36	0.98	1.60	2.23	2.85	3.47	4.09	4.72
Heat transfer rate	W/m^2	-14.05	1.10	16.25	31.40	46.55	61.70	76.85	92.00	107.15	122.30
Mass flow rate	kg/s	0.006	0.017	0.028	0.040	0.051	0.063	0.074	0.085	0.097	0.108
Calculated variables											
Average velocity	m/s	0.030	0.092	0.154	0.215	0.277	0.339	0.401	0.463	0.525	0.587
Convective coefficient	W/m^2K	-	0.68	5.05	6.50	7.23	7.66	7.95	8.16	8.32	8.44
Dimensionless parameters											
Nu		-	4.88	36.10	46.46	51.60	54.66	56.67	58.09	59.13	59.93
Ra		-	5.33×10^6	1.05×10^7	1.54×10^7	2.02×10^7	2.49×10^7	2.93×10^7	3.37×1^7	3.79×10^7	4.19×10^7
$(S/L)\ Ra_s \sin 45°$		-	4.31×10^5	8.47×10^5	1.25×10^6	1.64×10^6	2.01×10^6	2.38×10^6	2.73×1^6	3.07×10^6	3.39×10^6

Table 2. The calculated Nusselt number for the same value of channel aspect ratio (S/L = 0.1145).

	Nusselt Number							
Nu (this study)							47.58	61.05
Nu (Khedari et al., 2002)					36.64	54.90		
Nu (Gebhart, 1971)		2.38		8.12				
Nu (Azevedo & Sparrow, 1985)	5.38		10.88					
Rayleigh number	6.0E+04	1.5E+05	1.0E+06	7.8E+06	2.0E+06	8.0E+06	1.5E+07	4.2E+07

Note:

Nu (Azevedo & Sparrow, 1985) = $0.645[Ra\ (S/L)\ \cos 45°]^{0.25}$

Nu (Gebhart, 1971) = $1 + \left\{0.071 \cdot Ra^{1/3} \cdot \left(\frac{S}{L}\right)^{1/9} - 1\right\} \sin 45°$

Nu (Khedari et al., 2002) = $1.227 \cdot \left[\left(\frac{S}{L}\right) \cdot Ra \cdot \sin 30°\right]^{0.2916}$

of inclination (θ). Exploration of the experimental results of surface and air temperature shows two linear relationships with the solar intensity in a day, one relationship for low air temperature and another for high air temperature. Though the solar intensity is the heat source for the solar chimney, a simple data analysis of T_b, T_o-T_i, Q/A and $\dot{m}$ was carried out as linear function against T_h-T_b. In addition, the effect of cloud obstructing the solar radiation on the temperatures of air and hot surface are excluded by taking the correlation of non-dimensional group for $3.0^\circ C \leq T_h-T_b \leq 9.0^\circ C$ or the solar intensity of greater than 450 W/m^2. It was found that the values of convective heat transfer coefficient are in the range of 6.50-8.44 W/m^{2}K.

Determination of convective heat transfer coefficient is important in the simulation and investigation of performance of a solar chimney. With similar geometry of a solar chimney located in the practical field, this study proposes the correlations for determination of convective heat transfer coefficient and amount of mass flow rate developed in the solar chimney, the correlation between Nu_s and Ra_s and correlation between Re_s and Ra_s, respectively. The derived correlation between Nu_s and Ra_s is

$$Nu_s = 1.444 \cdot [(S/L) \cdot Ra_s \cdot \sin 45^\circ]^{0.249}$$

The power of 0.249 is close to the traditional value of 0.25 power found by Ostrach (1953). Comparing to previous studies in Azevedo and Sparrow (1985), Hirunlabh et al. (2001), Gebhart (1971), and Khedari et al. (2002), the proposed correlation is capable to calculate the Nu_s and the heat transfer coefficient in the high range of Ra_s values.

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