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An Investigation of Natural Convection of Air Flow through A Vertical Duct with Rectangular Cross-Section Heated from A Singled-Side.

دراسة السريان الطبيعي للهواء خلال نفق رأسي مستطيل المقطع مسخن من أحد جوانبه

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ملخص:
تم إجراء اختبار تجريبي لدراسة تأثير العوامل المختلفة على عملية التدفق الحر للهواء عبر القنوات الرأسية. تم تصميم وتركيب وحدة الاختبار التجريبية في معمل تكييف الهواء بكلية الهندسة جامعة المنصورة. تتكون طاولة الاختبار بشكل أساسي من مجرى عرضي مستطيل الشكل بعرض 25سم مع أسماك وارتفاعات مختلفة للمجرى. تتراوح سماكة مجرى الهواء من 3إلى 20سم في حين يتراوح الارتفاع بين 50 و 200سم. جميع جوانب مجرى الهواء معزولة بشكل جيد مع جانب واحد مسخن بكثافة فيض حراريتتراوح بين191و$440w/m^2$. تم رسم النتائج التجريبية في صورة علاقة بين معدل تدفق الهواء خلال المجرى والعوامل المختلفة تحت الدراسة ، أي سمك وارتفاع المجرى وكثافة الفيض الحراري. تظهر النتائج أن معدل تدفق الهواء يزيد مع كثافة الفيض الحراري وارتفاع القناة. يستنتج ايضا أن معدل تدفق الهواء يزيد مع سمك المجرى حتى يصل إلى قيم قصوى عند سمك 10سم ومن ثم ينقص مع زيادة إضافية في سمك المجرى.

Keywors: (Natural Convection, Vertical Duct, Rectangular Section and Air Flow)

Abstract:
An experimental investigation is made to study the effect of different parameters affecting the process of natural air flowing through vertical ducts. The experimental setup has been designed and installed in the Air Conditioning Laboratory, Faculty of Engineering, Mansoura University. The test rig is consisted of mainly of rectangular cross-section duct of 25 cm width with different heights and gap thicknesses. The air gap thickness ranges from 3 to 20 cm while the height is ranged from 50 to 200 cm. All duct sides are well insulated with one side heated under heat flux density ranges from 191.04 to $440.75 w/m^2$. Experimental results are plotted to indicate the relation between air volume flow rate through the vertical duct and different parameters discussed, namely, gap thickness, duct height and heat flux density. Based on measured results the air volume flow rate increases with increasing both heat flux density and duct height. It is concluded also that, the air volume flow rate increases with increasing the gap thickness until it reaches maximum values, namely at gap thickness of 10 cm and then decreases with further increase in gap thickness. The results of the present study could be useful in the design and application of buoyancy-assisted natural ventilation systems.

Introduction

Solar Chimney is a thermal-solar device which utilizes the solar energy to create natural ventilation. Solar chimney contains absorber material which functions to absorb and convert the solar radiation to thermal energy which heats up the air particle along the chimney channel. The heated air particle creates a medium with lower density and produces buoyancy force. When the solar chimney installed on a roof of a building with air access between the space and the chimney, buoyancy force updrafts the air along the chimney channel and natural circulation of air is formed in the specified space.

Khanal and Lei, (2011), presented an overview of solar chimney research that had taken place in the last two decades. The review focused on two main areas of research – the effects of geometry and inclination angle on the ventilation performance of a solar chimney. The experimental investigations of solar chimney had dominated the existing literature. However, numerical modeling of solar chimney using computational fluid dynamics (CFD) technique had attracted increasing attention. Moreover, this review found that solar chimney as a passive ventilation strategy had not been fully understood.

Ong (2003), proposed a simple mathematical model of a solar chimney. The physical model was similar to the Trombe wall. Steady state heat transfer equations were set up to determine the boundary temperatures at the surface of the glass cover, the rear solar heat absorbing wall and the air flow in the channel using a thermal resistance network. The thermal performance of the solar chimney as determined from the glass, wall and air temperatures, air mass flow rate and instantaneous heat collection efficiency of the chimney were presented. Satisfactory correlation was obtained with experimental data from other investigators, e.g. Hirunlabh et al.(1999).

Li, et al (2004),investigated heat transfer process and natural ventilation driven by a solar chimney attached to a sidewall of building ,with CFD technique in detail. They studied the chimney cavity width, wall temperature, height and breadth, the ratio of outlet area to inlet area as well as the outlet location of the solar chimney. They found that for given building geometry and inlet areas, there was an optimum cavity width at which a maximum airflow rate could be achieved. Based on the prediction, the airflow rate reached maximum when B/H was approximately 1/10, While ventilation flow rate was increased with increasing of chimney height.

Bassiouny, and Koura(2008),analytically and numerically studied the solar chimney concept used for improving room natural ventilation. Their study considered some geometrical parameters such as chimney inlet size and width, which were believed to have a significant effect on space ventilation. In addition, the average air exit velocity was found to vary with the intensity of heat flux.

Lee, and Strand,(2009), described the basic concepts, assumptions, and algorithms implemented into the Energy Plus program to predict the performance of a thermal chimney. Using the new module, the effects of the chimney height, solar absorptance of the absorber wall, solar transmittance of the glass cover and the air gap width were investigated under various conditions. Chimney height, solar absorptance and solar transmittance turned out to have more influence on the ventilation enhancement than the air gap width.

Yan, et al (2011), performed theoretical research and numerical simulation for ventilation properties of solar chimney with vertical collector and they were compared with experimental results. Results showed that. When the collector height was increased, the natural ventilation increased first and then decreases as the growing of the air layer thickness under the same chimney height and width; there existed an optimal ratio between heat collector height and width which made the ventilation largest.

Tan, and Wong (2013), examined the effect of the solar chimney’s stack height, depth, width and inlet position on the interior performance (air temperature and speed). Simulations showed that the output air temperature remained constant while the solar chimney’s width was the most significant factor influencing output air speed. Solar chimney’s inlet position had limited influence on the output air speed although regions near the solar chimney’s inlet showed an increase in air speed.

Zavala-Guillén, et al (2018), presented a conjugate heat transfer analysis of a double air channel solar chimney (SC-DC) aiming to determine the configuration that maximizes the mass flow rate of the system. They found that the optimal configuration of the SC-DC under the considered conditions was $L = 2\ m$ *and* $b = 0.125\ m$. The optimum L of the SC-DC was similar to the value reported for a conventional chimney, whereas the optimum b was smaller than the one of a conventional chimney.

Somsila, et al (2010), investigated the ventilation efficiency of solar chimney using experimental and computation fluid dynamics (CFD) methods. The influence of heat flux in a range of 400-800 W/m^2 and 1 to 2 m height of solar chimney on the ventilation efficiency was investigated. It was found that the ventilation efficiency and the volumetric air flow rate were increased with increasing the heat flux and height of solar chimney. In addition, CFD simulation showed good agreement with experimental results.

Amori, and Mohammed (2012), investigated numerically and experimentally heat transfer process and fluid flow in a solar chimney used for natural ventilation. Solar chimney was designed, manufactured and tested by selecting different positions of air entrance namely: bottom entrance, side entrance, and both side and bottom entrances. Experimental results showed that a solar chimney with side entrance gives better thermal performance. A comparison between the numerical and the experimental results showed fair agreement.

Imran (2017), mathematically and experimentally studied rooftop solar collector under different ambient conditions and different geometrical parameters. The model was converted to a FORTRAN computer program and solved by iteration matrix procedure. The experimental study of solar collector was built and set up. The results revealed that for 2 m height, 1 m width and different air gap depths (0.1, 0.15,and 0.2 m). The air volume flow rate was (100 to 280) m^3/h obtained under solar intensity varies from 200 to 800 W/$m^2$and inclination angle 60°. The results showed that there is an optimum size of 0.2 m air gap at which maximum ACH is resulted, and the most influencing parameter on the rooftop solar chimney performance is the solar radiation.

Chen, et al (2003), conducted experiments using an experimental solar chimney model with uniform heat flux on one chimney wall with a variable chimney gap-to-height ratio between 1:15 and 2:5 and different heat flux and inclination angles. Results showed that a maximum airflow rate was achieved at an inclination angle around 45° for a 200 mm gap and 1:5 m high chimney, and the airflow rate was about 45% higher than that for a vertical chimney at otherwise identical conditions.

Burek, and Habeb, (2007), reported on an experimental investigation into heat transfer and mass flow in thermo-syphoning air heaters, such as solar chimneys and Trombe Walls. The test rig comprised a vertical open-ended channel with closed sides, resembling a solar collector or solar chimney approximately 1 m^2.The channel depth was varied between 20 and 110 mm. They found that the mass flow rate through the channel was a function of both the heat input and the channel depth, and the thermal efficiency of the system (as a solar collector) was a function of the heat input, and independent upon the channel depth. Correlations for air mass flow rate and thermal efficiency were given in dimensionless forms.

Arce, et al. (2009), experimentally investigated thermal performance of a solar chimney for natural ventilation. The results showed that for a maximum irradiance of 604W/m^2,a maximum air temperature increment of 7 ℃ was obtained through the solar chimney. Also, a volumetric air flow rate ranging from50 to 374 m^3/h was measured. It was observed that the air flow rate through the solar chimney is influenced by a pressure difference between input and output, caused mainly by thermal gradients and wind velocity.

Punyasompun, et al. (2009), presented investigation on the use of solar chimney in high-rise building. To this end, two small scale models of a three stores building were built. The floor dimensions of each store were 1.2×2×1 m. Solar chimneys were integrated into the south-faced walls of one unit whereas the other unit served as a reference. First, a comparison between the SC building models and a common model without openings (SC) demonstrated that multi-stores solar chimney was a good alternative. Room temperature of the solar chimney model was lower than the room temperature of the common model, depending on the floor level by up to 5 °C.

Alzaed, and Mohamed (2014), experimentally studied the performance of a solar chimney to induce natural ventilation inside a test room placed in arid region. The experimental observations showed that, using a solar chimney can maintain the room at lower temperature than the ambient temperature with small variations along the day period. Along the day period, it was seen that, the values of the air velocity using air gap of5 cm width higher than that when using air gap of 10 cm width.

Jing, et al. (2015), carried out an experiment with a solar chimney model with large gap-to-height ratios between 0.2 and 0.6. An improved prediction method, which takes into account the variation of pressure loss coefficient for different flow conditions at the chimney outlet, was presented and compared with the experimental results obtained in their work and available in the literature. It was shown that the improved prediction method were in better agreement with the experiment results than the existing prediction method available in the literature for both narrow and wide chimneys. Experimental results showed that an optimum gap-to-height ratio around of 0.5 maximized the airflow rate in chimney.

Experimental Apparatus and Instruments

In order to investigate experimentally the effect of different parameters on ventilation rate of air, a test rig is designed and manufactured in Mechanical Power Engineering Department, Faculty of Engineering, Mansoura University.

The test rig shown in Fig.(1) consists of the test section (1), variable transformer (2),ammeter (3), volt meter (4), temperature measuring device (5), thermocouples (6), and wiring system (7). The ammeter (3) type (VEYRON VL9205 digital multi-meter) measures electric current ranged from 0.0 to20 A, with a minimum reading of 2mA and accuracy of ±1.2%.The voltmeter (4) type (VEYRON VL9205 digital multi-meter) measures electric volts ranged from 0.0 to 200 V, and an accuracy of ± 1.2 %.

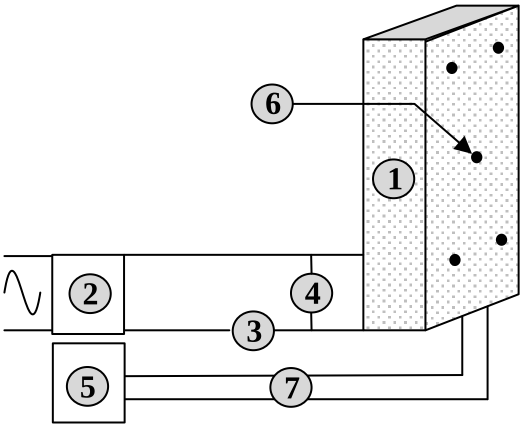


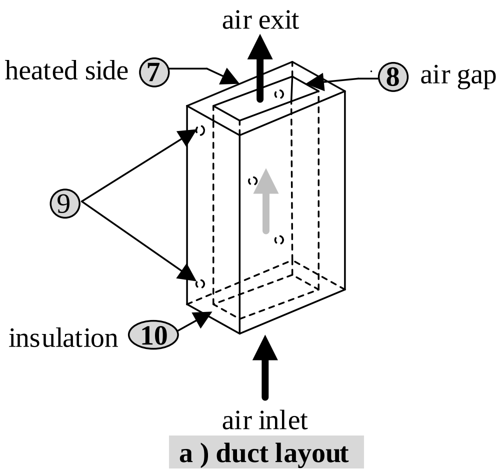
Fig (1) test rag diagrammatic representation

The variable transformer (2) type TROIDAC) capable of providing electric volts from 0.0 to 380 volts with endless steps was used. The temperature measuring device is a temperature recorder type (YOKOGAWA) with 24 channels capable of reading and recording the temperature reading of different thermocouple types (K and R) with a minimum reading of 0.1℃ and an accuracy of ± 0.3 **%.**

The test section (2) is shown in Fig. (2a) and consists of heated plate (8),air duct (9) thermocouples(10) and thermal insulation (11).

The heated plate (8) shown in Fig.(2-b) consists of galvanized steel sheet (12) of 1 mm thickness , 0.25 m width and 0.5 m. height fixed over a wooden farm (13) .The steel sheet is covered with mica sheet (14) of (0.5 mm) thickness to prevent contact between the steel sheet and the electric heater. The electric heater (15) is a wounded Nicklechrome resistance of 10Ωper part with a total resistance of 40 Ω. The heater is covered with a layer of mixture of sand and gypsum dough (16). The dough after completely dried is covered with glass-wool insulation (17).

Four heaters are used in this study to form four heated areas namely of 0.125, 0.25, 0.375 and 0.5 m^2.



a) duct layout

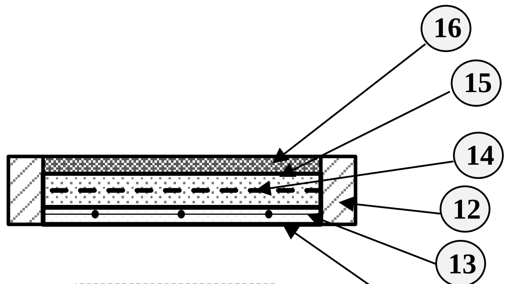
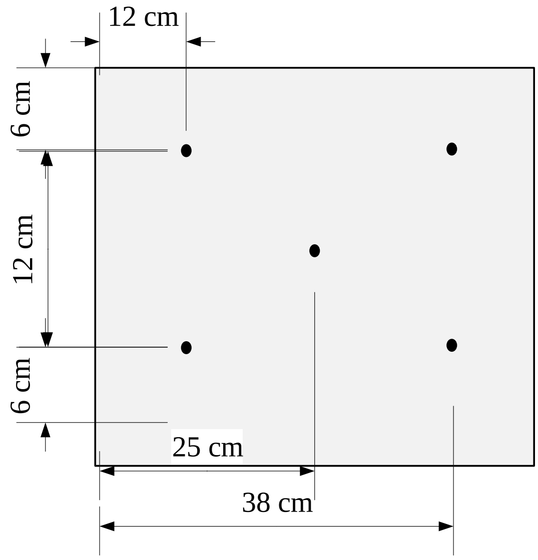


Fig (2-b)



C) thermo couple distribution

Fig (2) test section layout

Every steel sheet is provided with 5 type K thermo-couples (18) distributed as shown in Fig(2-c). The air gap of the test section can be changed with values of 3,5, 7, 10, 15 and 20 cm.

Experimental Procedure

Before starting the experiments the following steps are made;

1-Conect thermocouples leads to the temperature recorder;

2-Connect the heater leads to the transformer via ammeter and voltmeter;

3-Connect the transformer to the main electric supply;

4-Regulate the transformer to the predetermined voltage;

5-Open the electric circuit and let the system working until it reaches the steady state condition by monitoring the mean heated surface temperature;

6-when the system reaches the steady state condition register the readings of all connected thermocouples, the volt and ampere, and finally the Anemometer reading;

7-Change the transformer exit voltage to a higher value and repeat the steps 5 and 6.

8-Calculations of heat flux density and air flow rate using the following relations:

The heat flux density (q) added to the system can be calculated as:

$$\mathbf{q = (I \times V)/A}$$

where I is the current in ampere , V volt and A is the area of the heated plate in m^2.

The ventilation rate can be calculated as :

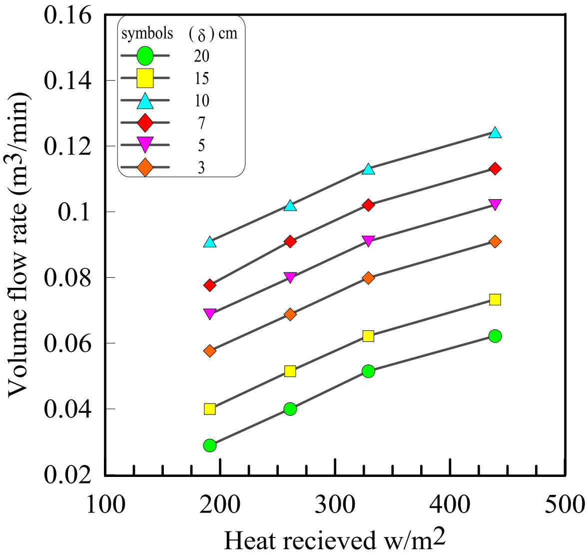
$$\mathbf{CMM = C \cdot A_a}$$

where CMM is the ventilation rate in m^3/min, C is the air velocity measured by the fan anemometer in **m/s** ,$\mathbf{A_a}$ is the cross-section area of anemometer in m^2.

Uncertainties of c, q and CMM are 7, 1.65 and 7.5% respectively.

Results and discussion

Four parameters are discussed in this work namely heat flux density (q), duct gap thickness (δ), total duct height (h_t), as well as heated height of the duct (h_h).



Fig(3) Relation between heat flux density and air volume flow rate for h= 50 cm, and various gap thickness value (δ) with 50 cm heated height

Effect of heat flux density

Figure (3) indicate the relation between ventilation rate (CMM) and heat flux density (q) at different gap thickness (δ) of 3,5,7,10,15 and 20 cm. It is shown from the figure that the ventilation rate increases with increasing heat flux density in the range of (189 to 441w/m^2).

The figure also shows that the ventilation rate is affected by the duct gap thickness at constant heat flux density.

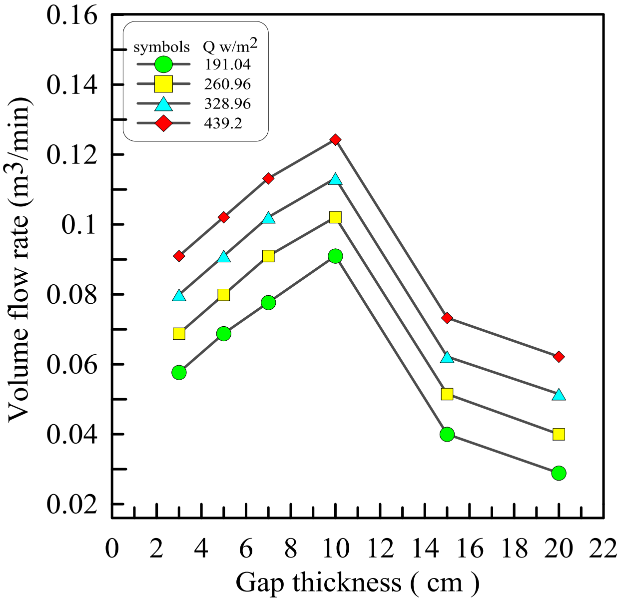


Fig (4) Relation between air volume flow rate and h=50 cmgap thickness at differen heat flux densities forwith 50 cm heated hieght.

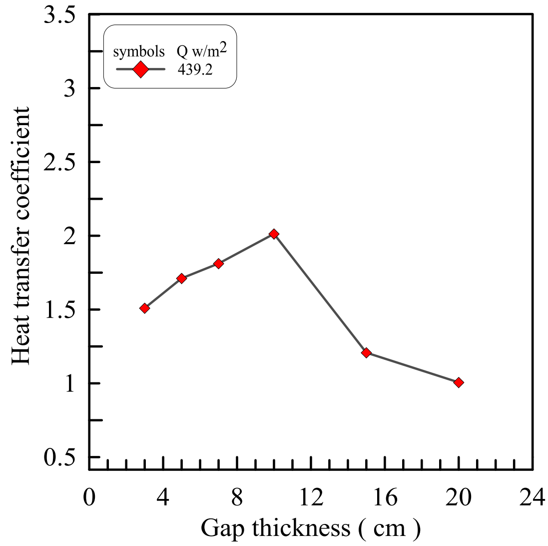
Effect of gap thickness

Figure (4) shows the effect of gap thickness on ventilation rate for heat flux density ranging from 189 to 441w/m^2. One can conclude from the figure that, ventilation rate increases with increasing the gap thickness until it reaches its maximum values, for different heat flux densities, at gap thickness equal to 10 cm. After reaching its maximum value, the ventilation rate begins to decrease with further increase of gap thickness.

The reduction of ventilation rate for gap thickness higher that 10 cm may be due to the decrease in chimney effect which is caused by the decrease of the air mean temperature difference across the duct. The decrease of temperature difference caused by the decrease of air mean outlet temperature is due to absence of heater effect on the air layer far away from the heated side. This decrease in outlet temperature leads to a decrease in convective heat transfer coefficient of air through the duct as shown in Fig. (5).

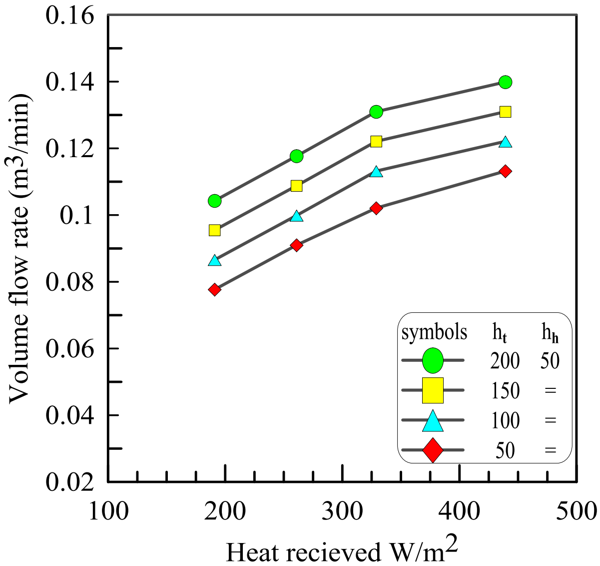
Effect of the duct height

Two groups of the experimental results will be demonstrated in this section which are illustrated in Figs. (6-8). The first group concerns the ventilation rate through the duct of different heights with constant heated area. The second group of results concerns the ventilation rate through duct of different heights with all their surfaces heated with constant heat flux density.



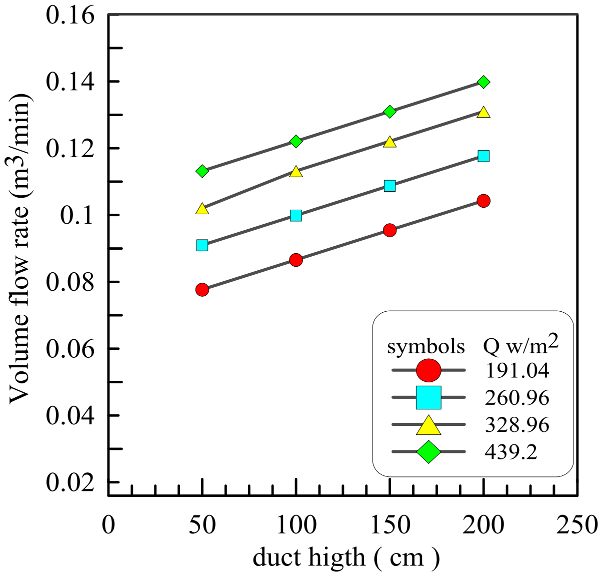
Fig(5) Relation between air Heat transfer coefficient and gap thickness at heat flux densities (439.2) for h= 50 cm with 50 cm heated height

The relation between ventilation rate and heat flux density through the ducts of heights 0.5, 1 ,1.5 and 2 m with the lower 25% of area heated with heat flux density ranging from 189 to 441w/m²is shown in Fig (6). It is shown from the figure that the ventilation rate increases with heat flux density and is affected by the height of the duct under constant value of heated area.



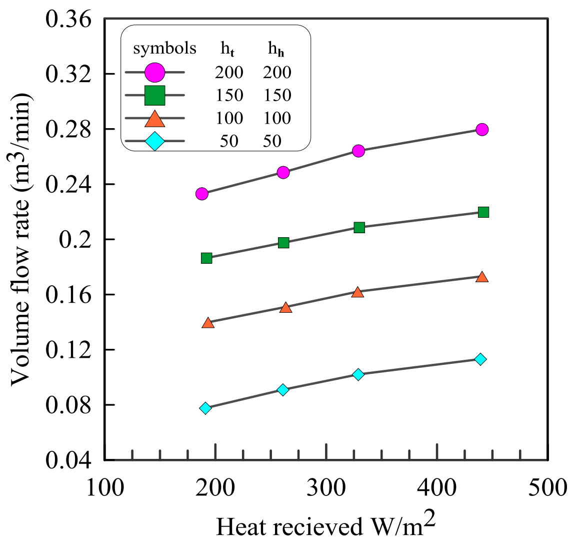
Fig(6) Relation between heat flux density and air volume flow rate for different total height at δ=7 cm and the lower area 50 cm height heated

Figure (7) shows the relation between ventilation rate and the height of duct at different values of heat flux density. The figure shows that the ventilation rate increases with increasing the duct height for different heat flux density. This indicates the chimney effect on ventilation rate.



Fig(7) Relation between air volume flow rate and hight at differen heat flux densities for δ= 7 cm the lower 0.50 cm height heated

Figure (8) shows the effect of heated plate height having a constant heat flux density on ventilation rate for different heat flux densities. It is concluded from the figure that the ventilation rate increases with increasing both heated height and heat flux density. The increase in ventilation rate in this case is higher than that of the case of 25% of the surface area of the duct heated.



Fig(8) Relation between air volume flow rate and heat recieved for different values of duct height with all the duct height heated,gap thickness δ=7cm

Conclusions

From the above results the following conclusions can be made:

1- The ventilation rate increases with the heat flux density added through the heated side of the duct.
2- The ventilation rate increases with the duct gap thickness until it reaches maximum values at gap thickness of 10 cm and then decreases with further increases in gap thickness.
3- The ventilation rate increases with the duct height when the lower 25% of the height is heated with different heat flux densities.
4- The increases in ventilation rate with duct height in the case of heating all the duct surface area is higher than the case of heating only 25% of the duct surface area for the same height.

Nomenclature

A	Surface area of the heated side, m^2
A_a	cross section area of anemometer fan, m^2
C	Anemometer velocity reading, m/s
h_h	Heated surface height, m
h_t	Duct height, m
I	Electric current, Ampere
V	Electric volt, volt
q	heat flux density, W/m^2
d	Air gap thickness, m

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