Effect of half circular obstacles in duct on natural heat transfer: numerical study

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Abstract
The natural heat transfer in ducts depend on generating an induced flow due to the difference in density between the heated fluid and it is environment. The effect of reduce cross sectional area of a vertical isothermal duct by adding half circular obstacles to the inner side of the duct. The effect of the induced flow and obstacles were study using COMSOL software and compared to heat through same duct with no flow. The results that obstacles increase induced flow by 16% compared to normal vertical duct, Also shows a reduction in value of the maximum temperature of the hot surface at the solar peak heat flux (3:00 PM).

Keywords: Natural convection, induced flow, duct flow, obstacles.

Nomenclature

\[ \begin{align*}
H & \quad \text{height of duct (m)} \\
\rho & \quad \text{density of fluid (kg/m}^3) \\
W & \quad \text{width of the duct (m)} \\
\mu & \quad \text{dynamic viscosity (kg/m.s)} \\
T_H & \quad \text{Temperature of hot surface (C)} \\
\beta & \quad \text{volumetric of thermal expansion (K}^{-1}) \\
T_C & \quad \text{Temperature of cold surface (C)}
\end{align*} \]
Introduction

In many applications, the heat generated in domain or transferred to it represents unwanted additive and getting rid of this heat in some cases could cost a large bill. In air conditioning application the amount of power used to cool down residential and office places and maintain a comfortable environment cost a lot, especially in hot countries where the demand on power has a significant increase in summer season (1). A close look at the heat load in any ordinary building will show that the external heat flux through walls and roofs to domain is the dominant part of the load(2, 3). Although, a good design and smart use of building material could slash a large slice of inward heat flux, the old building and unprofessional building design struggle with hidden economic consequences. The fix of such cases usually come as insulate the external wall of building(4-7). Most the time internal insulation is used, especially when use decorative designs of insulation, but the external wall which exposed to outside environment condition will absorb the heat during the day and release it during early hours after sun set. Using outdoor false decoration (envelope walls) with the continuous developing in building material become easier and cheaper. Envelope wall could be used as additional thermal resistance or a shade to eliminate the direction of wall towards the sun. Attached walls work as additional resistance to increase the overall wall heat resistance or in another word minimize over all heat transfer coefficient which slow the rate of transferred heat to building and reduce the heat load or work (8-11). Another scenario envelope walls work as shade in front of building sides that face the sun for long time during the day(12). Although, A huge amount of researches are published in every corner of this concepts the developing in building material and some physical concepts allow for more work to be done. In most recent work, (13) conducted a numerical comparative study of a different building material on the thermal performance of the building external walls, in this study authors put a guide for designers to fellow to find the optimal thickness and material. While (14) study the effect of contents on reinforced ash fly/cement board on thermal performance and use orthogonal test to test it is reliability on construction. Tamene Y. studied using a parallel layers of different material to enhance the insulation and conclude that using 5cm air gap with any insulation wall will significantly enhance the insulation and for the internal wall the recommended using glass wool because it is cheaper than cork(4). Congedo PM conducted an experimental study to demonstrate the best solution that designers could adaptive to optimize the
comfortable internal environment based on long term monitoring of internal temperature in sole building, they conclude that the best option is to use a double layer of tuff for the external walls and compact layer for the internal walls (15). Also, Alaboud M (16) compare the cooling load of two residential building in Mecca Sudai arabia one with external insulated and the other is normal building, the results show that using insulation wall can chop 50% of the cooling load. Another approach is using the decorative walls as a shade and use the air gap between the building and the decorative walls. Shaik S. use MATLAB to simulate the effect of seven building material on the cooling load of a building the results show that regardless of the material using vertical air gap in external wall can significantly reduce the cooling load of the building (17). Zhuang Z use a numerical model to study the effect of heavy ventelated wall on the thermal performance and thermal load of building under different enviroment condition his conclusion is the ventalated wall has it is potential in optimize the internal zone temperature (18). Hussein MS conducted a numerical study to investigate the shape of the induced laminar flow in vertical duct with one side heated wall and also study different aspect ratio of the duct width to duct length the result presents a flow rate correlation form (19). Hussein MS’s (19) study showed that the induced flow profile is shifted towards the hot wall and the density difference inside the duct accelerates the natural convection. In this study a numerical study to investigate the effect of use half circular obstacles in cold side of isothermal duct with one heated side by solar heat flux on induced flow rate and flow shape and natural convection using COMSOL software. The duct represents the outer layer of insulation fixed over external walls to reduce heat transfer through it.

**Induced flow in duct**

The physical concept of the study is a two dimension duct with high aspect ratio (width to height) to insure fully developed flow at the exit. The duct width (w) is 2 cm and the height (H) is 1m, one side of the duct is exposed to solar heat flux and the wall temperature (\(T_{hi}\)) changes during the day the other side which is fixed in whole contact with building external wall has temperature (\(T_c\)) and it has many half circular protuberance that represent an obstacle to the induced flow rate as shown in figure 1. The radius of half is 2.5 mm and these obstacles cause an increase in internal wall area by 15%. The laminar flow inside the duct due the low speed of the induced flow cancels the effect of The effects of compressibility and viscous dissipations. For the Boussinesq approximation, the governing equations for two dimensional, steady, and laminar flow

Continuity:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad \text{..........................................................} \quad 1
\]

x-momentum
\[
\rho \left( u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( \mu \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu \frac{\partial u}{\partial y} \right) \quad \text{..........................2}
\]

y-momentum
\[
\rho \left( u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left( \mu \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu \frac{\partial v}{\partial y} \right) + \rho g \beta (T - T_0) \quad \text{.........3}
\]

Energy:
\[
u \frac{\partial (\rho C_p T)}{\partial x} + v \frac{\partial (\rho C_p T)}{\partial y} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) \quad \text{..........................4}
\]

Where \( \mu \) is the dynamic viscosity, \( \beta \) is volumetric thermal expansion coefficient, \( c_p \) is the specific heat at constant pressure and \( k \) is thermal conductivity.

The boundary conditions of the studied case are illustrated in figure 1 and Eq.5. The right wall which assumed to be exposed to external heat flux (solar heat flux) and temperature \( T_H \), the other wall is assumed to has a fix temperature \( T_c \) and it was taken to be indoor temperature to increase horizontal heat flow. The heating of the duct will cause in density difference and induce the flow to move up and the duct assumed to be open at the two ends, so the flow assumed to enter from the lower open and leave the duct from top. The exit of the duct assumed to be at ambient temperature and pressure. The gravity \( (g) \) effects is downwards in vertical direction and the condition of the velocity at walls was taken as no slip condition.

\[
0 \leq x \leq w, y = 0 \quad \frac{\partial u}{\partial y} = 0, \quad \frac{\partial v}{\partial y} = 0, \quad \frac{\partial T}{\partial y} = 0
\]

\[
0 \leq x \leq w, y = w \quad \frac{\partial u}{\partial y} = 0, \quad \frac{\partial v}{\partial y} = 0, \quad \frac{\partial T}{\partial y} = 0
\]

\[
0 \leq y \leq H, x = 0 \quad u = 0, \quad v = 0, \quad T = T_H
\]

\[
0 \leq y \leq H, x = w \quad u = 0, \quad v = 0, \quad T = T_c \quad \text{.........................5}
\]

These boundary conditions are used as input data to COMSOL software.

![Figure 1 Sketch of vertical duct and boundary conditions.](image)
Results and Discussion

The most important output of the numerical solution of the studied case is represented here. In figures 2, 3, 4 shows the temperature distribution inside the duct at (15:00 or 3:00 PM) and it is significant clear that the hot surface is the side of the solar heat flux, however the effect of the physical can be seen clearly, in figure 2 where the duct assume to closed from upper and lower ends the trapped air worked as insulation material and the heat is transferred from hot surface to cold surface by conduction. While in figures 3, 4 where the ends of the ducts are open and there is induced air flow, the maximum temperature in figure 2 is less compared to figure 1 due the natural convection that happened because of the moving air in duct by density difference. The air next to hot surface receive more heat than the air next to cold surface which makes a difference in density of the air inside the duct, this difference translated to moving of air upwards and the continuity of this phenomenon will replace the air in duct and bring fresh air with ambient temperature which help to remove more heat away from going inside the building.

![Figure 2](image1.png)  
**Figure 2** Temperature contour for closed duct (at 3:PM).

![Figure 3](image2.png)  
**Figure 3** Temperature contour for open ended duct (at 3:00 PM)
In figure 4 the presence of the obstacles lower the maximum temperature more than in figure 3 (from 63.8°C to 61.3°C) due to decrease the cross sectional area of the duct forced the flow to increase its velocity. Due to flow in channel the heat transfers to the wall of the building by convection which is lower than the conduction. The effect of the change in daily solar heat flux on the performance of the heat transfer in the duct will be left for the extension of this work in near future.

In figures 5 and 6 the effect of heat flux on flow is shown. In both figure the shift of velocity contour is obvious. The higher values of the velocity are shifted towards the hot side of the duct due to the density difference. Figure 6 shows the effect of the obstacles, where obstacles work on reduce the cross section area of the duct. Reducing the cross sectional area provokes the fluid to increase its velocity as continuity equation states. The increase in velocity is around 16% from 0.3 m/s to 0.35 m/s.
Conclusions

The main points that have been focused on in this study are the effect of the induced fluid flow in duct shape and obstacles on inner surface of duct, considering that the possibility of use the natural convection futures in improving the insulation material at external walls. The primary conclusions that can be extract from result are:

1. The induced fluid flow can remove away a part from the heat flux that hit the external wall and do not transfer it to the building.
2. Use regular shape obstacles on the inner cold side of the duct help to increase the velocity of the induced flow and remove more heat.
3. Although the obstacles increase the surface area of heat transfer surface, the gain still justifiable.

References

1. Hamoda MF, editor Role of Green Buildings in Reduction of Energy Consumption. 2020; Cham: Springer International Publishing.
2. Ali H, Al-Hashlamun R, editors. Building Envelope Thermal Upgrade for School Buildings in Jordan. IOP Conference Series: Earth and Environmental Science; 2019: IOP Publishing.
3. Rad EA, Fallahi EJC, Materials B. Optimizing the insulation thickness of external wall by a novel 3E (energy, environmental, economic) method. 2019;205:196-212.
4. Tamene Y, Serir LJUoH, Technology. Thermal and economic study on building external walls for improving energy efficiency. 2019;37(1):219-28.
5. Kisilewicz T, Fedorczak-Cisak M, Barkanyi TJE, Buildings. Active thermal insulation as an element limiting heat loss through external walls. 2019;205:109541.
6. Salavatian S, D’Orazio M, Di Perna C, Di Giuseppe E. Assessment of Cardboard as an Environment-Friendly Wall Thermal Insulation for Low-Energy Prefabricated Buildings. Sustainable Building for a Cleaner Environment: Springer; 2019. p. 463-70.
7. Yang J, Wang J, Xiong F, Liang H, Li YJJoTS. Assessment of Building External Wall Thermal Performance Based on Temperature Deviation Impact Factor under Discontinuous Radiant Heating. 2019;28(6):1129-40.
8. American Society of Heating R, Air-Conditioning E. 2017 ASHRAE handbook2017.
9. Huang J, Lv H, Feng W, Qu P, Huang ZJES, Part A: Recovery, Utilization,, Effects E. Determination of economical thermal insulation thickness for a building wall with two parallel structures. 2020;42(4):399-409.
10. Juanicó LEJC, Materials B. Thermal insulation of roofs by using multiple air gaps separated by insulating layers of low infrared emissivity. 2020;230:116931.
11. Kallioğlu MA, Ercan U, Avcı AS, Fidan C, Karakaya HJES, Part A: Recovery, Utilization,, Effects E. Empirical modeling between degree days and optimum insulation thickness for external wall. 2020;42(11):1314-34.
12. Hachim DM, Alsahlani A, Eidan AAJAIN, Sciences A. Measurements of wind and solar energies in Najaf, Iraq. 2017;11(9):110-7.
13. Jannat N, Hussien A, Abdullah B, Cotgrave AJJoS. A Comparative Simulation Study of the Thermal Performances of the Building Envelope Wall Materials in the Tropics. 2020;12(12):4892.
14. Zhanhua Z, Changyu S, Chao Z, An W, Shan Z, editors. Research on Decorative and Integrated Thermal Insulation Board for External Wall. E3S Web of Conferences; 2020: EDP Sciences.
15. Congedo PM, Baglivo C, Centonze GJJBE. Walls comparative evaluation for the thermal performance improvement of low-rise residential buildings in warm Mediterranean climate. 2020;28:101059.
16. Alaboud M, Gadi MJFC, Environment. The Effect of Thermal Insulation on Cooling Load in Residential Buildings in Makkah, Saudi Arabia. 2020;6(1).
17. Shaik S, Nagaraju S, Rizvan SM, Gorantla KK. Optimizing Vertical Air Gap Location Inside the Wall for Energy Efficient Building Enclosure Design Based on Unsteady Heat Transfer Characteristics. Soft Computing for Problem Solving: Springer; 2020. p. 1003-9.
18. Zhuang Z, Ying J, editors. THERMAL PERFORMANCE OF A HOUSE WITH VENTILATED WALL. Proceedings of 11th International Conference on Applied Energy,; 2019; Sweden
19. Hussein MS. Numerical Simulation for Laminar Natural Convection with in a Vertical Heated Channel Eng & Tech Journal. 2011;29(11).