A Study of Natural Convection Flow Through Rectangular Building with Four openings induced by Stack- driven forces

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Abstract *— The paper studies the natural convection of stack- driven airflow through rectangular building with Four opening. The dimensionless model of momentum and energy equations are analysed, using second order linear differential equation to develop the explicit expression for velocity, temperature profiles together with volumetric and mass- transfer by means of Laplace transform and variation of parameter method. Some numerical examples are presented graphically in order to illustrate the effects of physical parameters involved in the study. From the course of investigation, it was observed air temperature and velocity increase with the decrease in both parameters* (θ_0) *and* (Pr). *While, velocity increase with the increase in both parameters* (C_d) *and* (Gr) *Respectively.*

Keywords — *Stack- driven forces, Natural convection flow, Rectangular building, Four openings.*

I. INTRODUCTION

From a technological point of view, a study of natural ventilation in building is always important. The analysis of such flows finds application in different areas such as Fluid dynamics, architectural design and Engineering. Natural ventilation of building provides improvement of internal comfort and air quality conditions leading to a significant reduction of cooling energy consumption. Design of natural ventilation systems for many types of building is based on buoyancy forces. However, external wind flow can have significant effects on buoyancy-driven natural ventilation. Air flow distributions in buildings are considered to be as a result of the knowledge of the exact air supply to a building. Knowledge of the exact air supply to a building is necessary to determine its thermal performance and the concentration of the indoor pollutants. The exchange of air can be achieved either by mechanical means (Mechanical ventilation) or through the large opening of the building envelope (Natural ventilation). Of course natural ventilation is being pursued by humans, who are increasingly spending more time indoors, to extend the possibilities of living in uncongenial or squally conditions etc.

The improvements of the quality of the interior space both in its attractiveness, spaciousness, luminosity, and more importantly its proper natural ventilation are major concerns for designers of modern structures. Air flow modelling gives Architectures and Engineers the luxury to consider several design options in the minimum amount of time. As a result, the final design is not based on a tentative approach, but is a result of a professional design process considering several options and selecting the optimum solution. This can save on capital and running costs save time on commissioning. Many attempts to investigate this phenomenon have been made by some researchers such as, neutral zone in ventilated building was studied by [1]. [2] studied heat transfer by natural convection. Airflow process in single-sided natural ventilation was studied by [3]. An investigation of air flow rate across a vertical opening which is induced by thermal source in a room was given by [4]. Stack- driven airflow through rectangular cross- ventilated building with two openings using analytic technique was presented by [5]and steady airflow through multiple upper openings inside a rectangular building in the presence of indirect flow was also investigated by [6]. An example of solution multiplicity in a building with bi-directional flow openings was presented by [7]. CFD model of airflow air indoor pollutant in rooms was presented by [8]. A room airflow distribution system using CFD was presented by [9]. An approach with advantages and disadvantages of various methods for modelling air flow in the building was described by [10]and also studies buoyancy-driven natural ventilation of buildings-impact of computational domain. Displacement ventilation (where the interior is stratified**)** was presented by [11] and the mixing ventilation (where the interior has uniform

temperature) was presented by [12]. Airflow process that combined the ideas of displacement ventilation from [14] was studied by [13]. Mathematical modelling of wind forces was developed by [15].
ventilation driven by a point source of buoyancy on the floor of an enclosure in the presence of wind was examined by [16]. natural ventilation potential by considering thermal comfort issues was presented by [17]. heat and mass- transfer through an openings by natural convection in a single sided ventilated building was studied by [18] and the study also obtained an equation that predicts velocity distributions, volumetric airflow and mass transfer in terms of stack-effect using Bernoulli's equation for an in viscid fluid. 3D unsteady Reynolds-averaged Navier-Stokes (RANS) CFD simulations to reproduce the decay of CO_2 (Carbon dioxide) concentration in a large semi-enclosed stadium was presented by [19]. a study of two openings naturally ventilated building potential model considering solution multiplicity, window opening percentage, air velocity and humidity in China was presented by [20]. An experiment on the exchange flow through a window in a heated, sealed room of a test house was performed by [21]. The data give a smaller value of discharge coefficient$C_d = 0.044 + 0.004\Delta T$ and suggested that the reduction was caused by mixing of the incoming and outgoing air at the window.
Full- scale experimental and CFD methods were used to investigated buoyancy- driven single sided natural ventilation with large openings by [22]. A building having two openings at different vertical level on opposite walls with heights of the two openings are relatively small was studied by [23]. Natural ventilation induced by combined wind and thermal forces was studied by [24]. Wind driven cross ventilation in buildings with small openings was studied by [25]. A simple mathematical model of stack ventilation flows in multi-compartment buildings was presented by [26]. A study of natural ventilation in an enclosure containing two buoyancy forces was presented by [27]. A macroscopic model that describes natural convection through rectangular openings in partition-I in a single sided ventilated building was investigated by [28]. A macroscopic model that describes natural convection through rectangular openings in partition-II in a single sided ventilated building was also presented by [29]. A study of fluid mechanics of natural ventilation was given by [30]. A transient investigation of airflow through two upper openings in a cross ventilated rectangular building in the absence of opposing flow was study by [31].

The main objective of this study is to presents the effect stack- driven airflow through rectangular building with four openings. In which, the dimensionless model of momentum and energy equations are analysed to develop the explicit expression for velocity, temperature profiles together with volumetric and mass- transfer in the building. The result of the computations will be present graphically and various parameters such as Effective thermal coefficient (θ_0), Prandtl number(Pr), Grashof number (Gr) and discharge coefficient (C_d) embedded in the problem will be discuss. In addition, analysis with results obtained from the study will be perform in order to ascertain the best for optimal ventilation.

II. BUILDING DESCRIPTION

The study considered a natural convection flow in rectangular building with four openings with the effect of stack- driven forces. The building envelope has air as the connecting fluid and separated from one another by vertical openings of height (Y) and constant width of the vents (X_w) which is shown in Fig. 1. The density, velocity, temperature and pressure of air maintained atρ_0, U, T and P. And schematic diagram of air flow on the lower and upper openings is shown in Fig. 2.

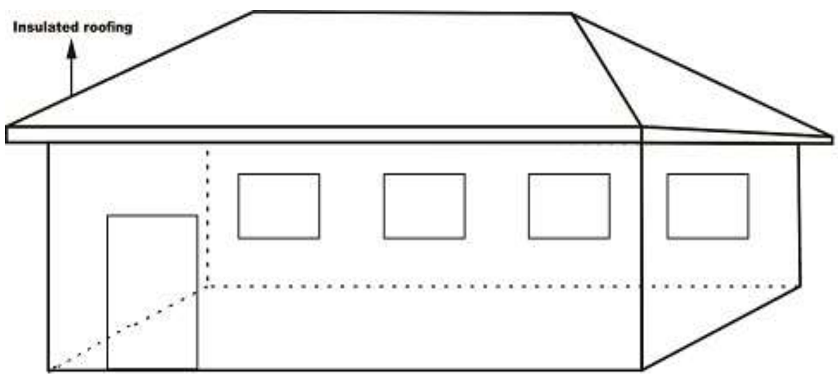

Fig. 1 Diagram of the building envelope

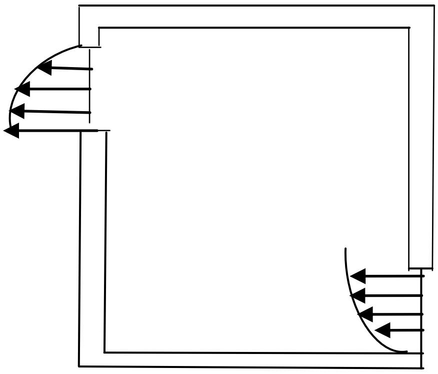

Fig. 1 Schematic diagram of air flow on the openings.

III. PROBLEM STATEMENT AND MATHEMATICAL FORMULATION

The preliminary assumptions worked in the study are, flow is assumed to be depend on the height of the vents, steady flow with no internal source so as the density of air will be nearly constant like incompressible fluid $(\rho_0 \approx constant)$ and the pressure be a component along the width of the vents in the building. Under the usual assumption of reduced gravity, the governing equations in dimensional form of the momentum and energy equations are,

$$v\frac{d^2u}{dy^2} + g\beta\Delta\theta = 0 \tag{1}$$

$$\alpha\frac{d^2\theta}{dy^2} = 0 \tag{2}$$

The momentum and energy equations in equations (1) and (2) are transformed into dimensionless form by scaling y with YL, u with $\frac{Ug\beta\Delta TL^2}{\alpha}$ and introducing θ with $T\Delta T + T_a$

$$Pr\frac{d^2U}{dY^2} = -GrT \tag{3}$$

$$\frac{d^2T}{dY^2} = 0 \tag{4}$$

The appropriate boundary conditions are introduced as

$$U = 0, T = -\theta_0 \text{ at } Y = 0 \text{ and } U = 0, T = 1 - \theta_0 \text{ at } Y = 1 \tag{5}$$

To obtain the temperature distributions, one need to consider the energy equation in (4) as

$$T'' = 0 \tag{6}$$

by taking the Laplace of both sides,

$$\mathcal{L}\{T''\} = \mathcal{L}\{0\} \tag{7}$$

Where,

$\mathcal{L}\{T''\} = S^2\mathcal{L}\{T(Y)\} - SC_0 - C_1$ and $\mathcal{L}\{0\} = 0$

We obtain the Laplace as

$$K(S) = \frac{SC_0}{S^2} + \frac{C_1}{S^2} \tag{8}$$

by taking the Laplace inverse in equation (8) we have,

$$T(Y) = C_0 + C_1 Y \tag{9}$$

applying boundary condition (5), we obtain the solution for temperature distributions as,

$$T(Y) = Y - \theta_0 \tag{10}$$

where, $C_0 = -\theta_0$, $C_1 = 1$ and $K(S) = \mathcal{L}\{T(Y)\}$

To obtain the velocity distributions, one need to consider the momentum equation in (3) as

$$U'' = -\frac{Gr}{Pr}(Y - \theta_0) \tag{11}$$

We observed equation (11) is non homogeneous, to solve one need to take the auxiliary equation of the homogeneous part;

$$U'' = 0 \tag{12}$$

Equation (12) yields to complimentary solution as

$$U_c = C_2 + C_3 Y \tag{13}$$

applying the variation of parameter methods, one can write the particular solution $U_p(Y)$ of equation (11) as,

$$U_p(Y) = V_1 Y_1 + V_2 Y_2 \tag{14}$$

Equation (14) yields to

$$U_p = \frac{Gr}{Pr}\left(\frac{\theta_0 Y^2}{2} - \frac{Y^3}{6}\right) \tag{15}$$

Where,

$V_1 = \frac{Gr}{Pr}\left(\frac{Y^3}{3} - \frac{\theta_0 Y^2}{2}\right), V_2 = -\frac{Gr}{Pr}\left(\frac{Y^2}{2} - \theta_0 Y\right)$ and the Wroskian $W(Y_1, Y_2) = 1$

The general solution of equation (11) is given by

$$U(Y) = \frac{Gr}{Pr}\left(\frac{\theta_0 Y^2}{2} - \frac{Y^3}{6}\right) + C_2 + C_3 Y \tag{16}$$

applying boundary condition (5), we obtain the solution for velocity distributions as,

$$U(Y) = \frac{Gr}{Pr}\left(\frac{\theta_0 Y^2}{2} - \frac{Y^3}{6} - \frac{(3\theta_0 - 1)Y}{6}\right) \tag{17}$$

Where, $C_2 = 0$ and $C_3 = -\frac{Gr}{Pr}\left(\frac{\theta_0}{2} - \frac{1}{6}\right)$

Volumetric air flow is given by

$$Q(Y) = \frac{A^* Gr c_d}{Pr}\int_{n=0}^{n=\frac{Y}{2}}\left(\frac{\theta_0 n^2}{2} - \frac{n^3}{6} - \frac{(3\theta_0 - 1)n}{6}\right)dn \tag{18}$$

Which yields to,

$$Q(Y) = \frac{A^* c_d Gr}{Pr}\left(\frac{\theta_0 Y^3}{48} - \frac{Y^4}{384} - \frac{(3\theta_0 - 1)Y^2}{48}\right) \tag{19}$$

Therefore, mass- transfer is given by,

$$m(Y) = \frac{A^* \rho_0 c_d Gr}{6Pr}\left(\frac{\theta_0 Y^3}{48} - \frac{Y^4}{384} - \frac{(3\theta_0 - 1)Y^2}{48}\right) \tag{21}$$

Notations and Greek's words

C_0, C_1, C_2, C_3 coefficients
A^* total area of the openings in non- dimensional Form
L line scale
g acceleration due to gravity
X_w constant width of the opening
y height of the opening in dimensional form
Y height of the opening in non- dimensional form
C_d discharge coefficient
u velocity of air in dimensional form
U velocity distribution in non- dimensional form

Greek symbols

ρ_0 ambient density of air
T_a ambient temperature of air
θ_0 effective thermal coefficient
θ air temperature in dimensional form
$\Delta\theta$ change of air temperature in dimensional form
T temperature distribution in non- dimensional form
ΔT change of air temperature in non- dimensional form
β coefficient of thermal expansion
α thermal conductivity ratio
ν kinematic viscosity of fluid

Non dimensional Group

Pr Prandtl number
Gr Grashof number

Subscript

w width of the openings

IV. NUMERICAL EXAMPLES

Analyses of the results obtained from equations (10), (17), (19) and (21) are plotted. The analysis of the results is done in order to see the effect of changes of parameters such as involved in the study to the overall flow across the vents while keeping other physical parameters and operating condition fixed. In this section there are Four parameters of interest in the study which includes, effective thermal coefficient (θ_0), Prandtl number (Pr), Grashof number (Gr) and discharge coefficient (C_d) respectively. The values used for θ_0 is $0.1, 0.3$ and 0.5. Similarly for Pr is between is $0.650, 0.710$ and 0.770, the value for C_d is between $0.60, 0.675$ and 0.750 the value for Gr is selected arbitrary between $1.00, 2.00$ and 3.00.

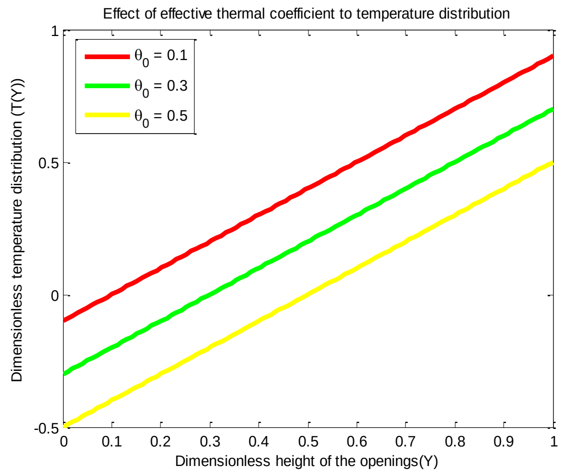

Fig. 3 Temperature distribution $\boldsymbol{T}$ versus $\boldsymbol{Y}$ for different values of $\boldsymbol{\theta_0}$

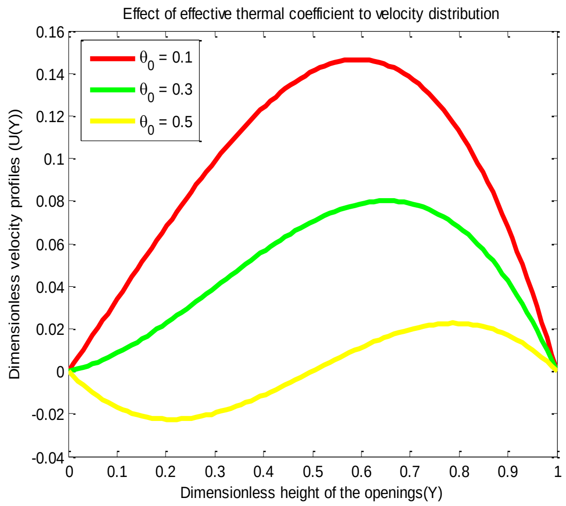

Fig. 4 Velocity distribution $\boldsymbol{U}$ versus $\boldsymbol{Y}$ for different values of $\boldsymbol{\theta_0}$with fixed values of $\boldsymbol{Pr = 0.710}$ and $\boldsymbol{Gr = 2.0}$

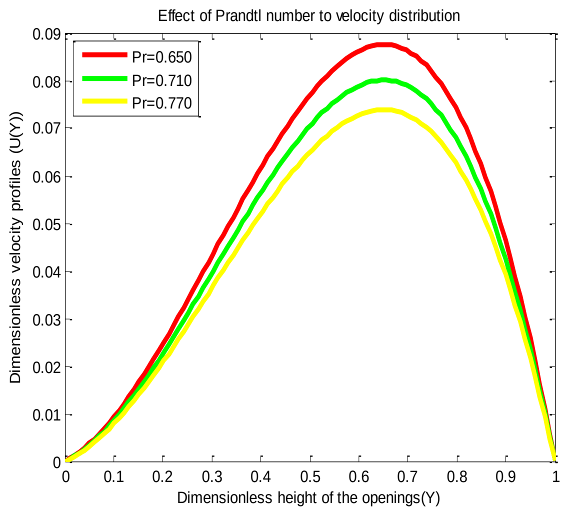

Fig. 5 Velocity distribution $\boldsymbol{U}$ versus $\boldsymbol{Y}$ for different values of $\boldsymbol{Pr}$ with fixed values of $\boldsymbol{\theta_0 = 0.3}$ and $\boldsymbol{Gr = 2.0}$

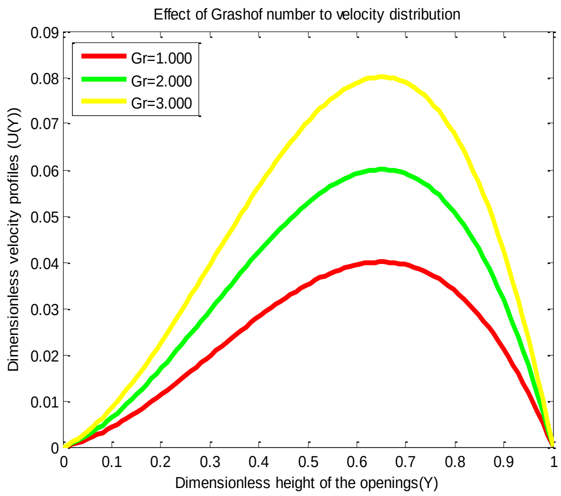

Fig. 6 Velocity distribution U versus Y for different values of Gr with fixed values of $\theta_0 = 0.3$ and $Pr = 0.710$

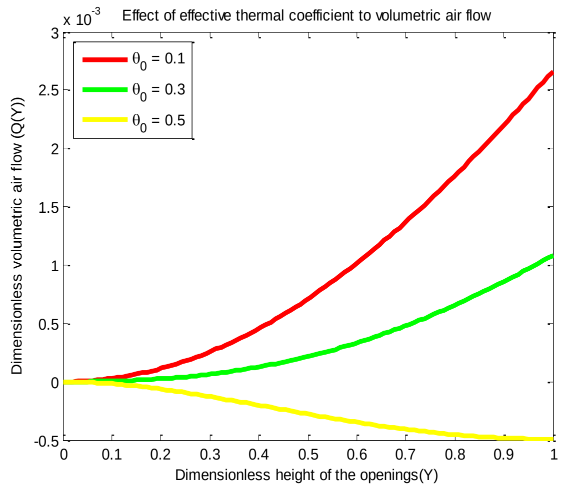

Fig. 7 Volumetric airflow Q versus Y for different values of θ_0 with fixed values of $Pr = 0.710, C_d = 0.6$ and $Gr = 2.0$

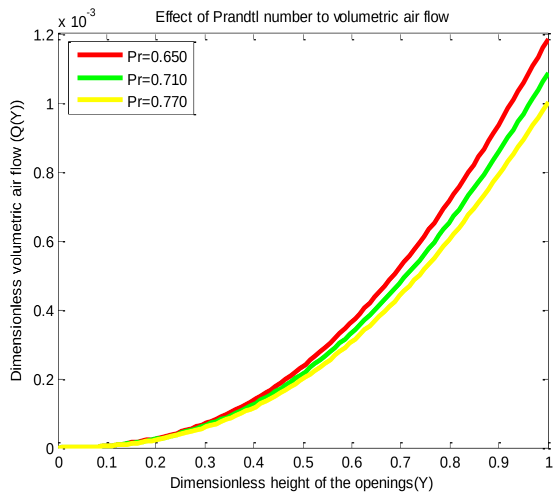

Fig. 8 Volumetric airflow Q versus Y for different values of Pr with fixed values of $\theta_0 = 0.3, C_d = 0.6$ and $Gr = 2.0$

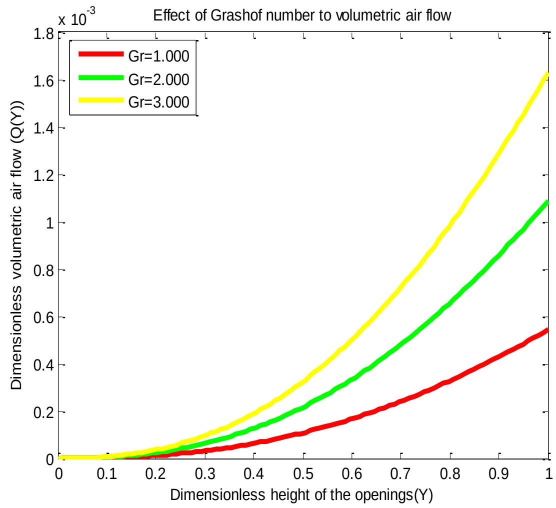

Fig. 9 Volumetric airflow $\boldsymbol{Q}$ versus $\boldsymbol{Y}$ for different values of $\boldsymbol{Gr}$ with fixed values of $\boldsymbol{\theta_0 = 0.3, C_d = 0.6}$ and $\boldsymbol{Pr = 0.710}$

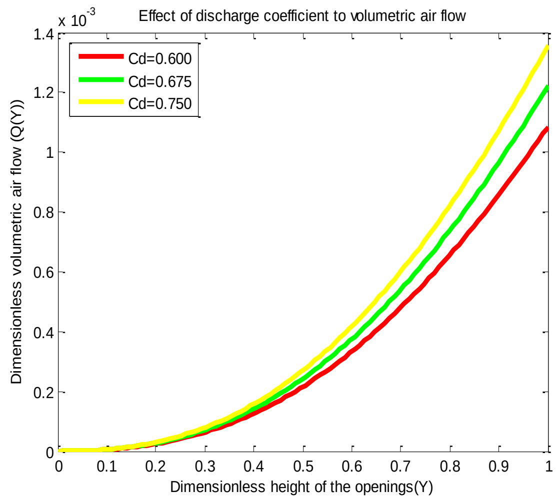

Fig. 10 Volumetric airflow Q versus Y for different values of $\boldsymbol{C_d}$ with fixed values of $\boldsymbol{\theta_0 = 0.3, Gr = 2.0}$ and $\boldsymbol{Pr = 0.710}$

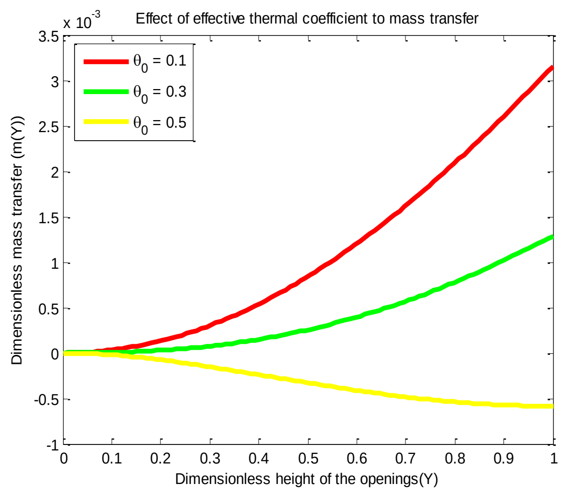

Figure 11: Mass transfer $\boldsymbol{m}$ versus $\boldsymbol{Y}$ for different values of $\boldsymbol{\theta_0}$ with fixed values of $\boldsymbol{Pr = 0.710, C_d = 0.6}$ and $\boldsymbol{Gr = 2.0}$

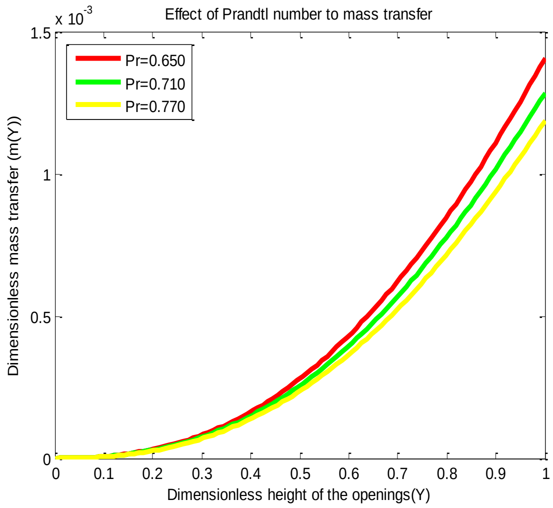

Fig. 12 Mass transfer m versus Y for different values of Pr with fixed values of $\theta_0 = 0.3, C_d = 0.6$ and $Gr = 2.0$

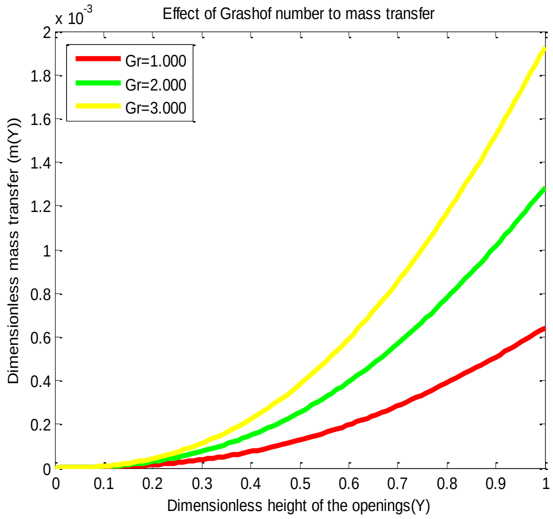

Fig. 13 Mass transfer m versus Y for different values of Gr with fixed values of $\theta_0 = 0.3, C_d = 0.6$ and $Pr = 0.710$

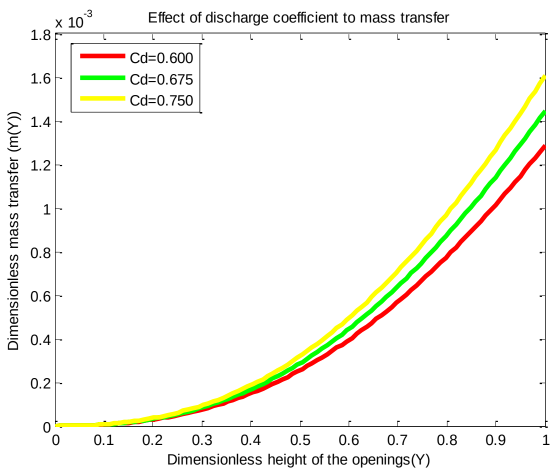

Fig. 14 Mass transfer m versus Y for different values of C_d with fixed values of $\theta_0 = 0.03, Gr = 20$ and $Pr = 0.710$

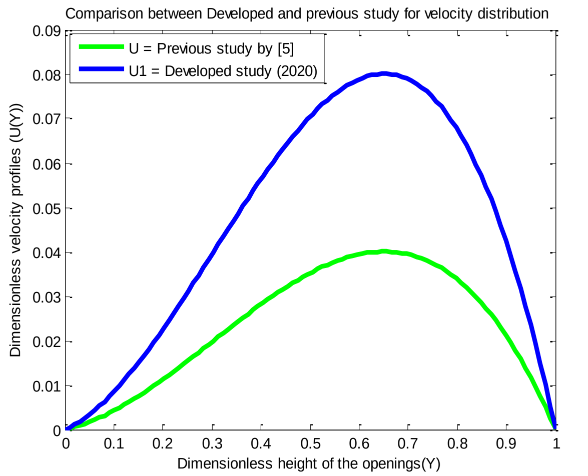

Fig. 15 Comparison between velocity distribution U and $U1$ for fixed values of

$\theta_0 = 0.3, Pr = 0.710, C_d = 0.60$ and $Gr = 2.0$

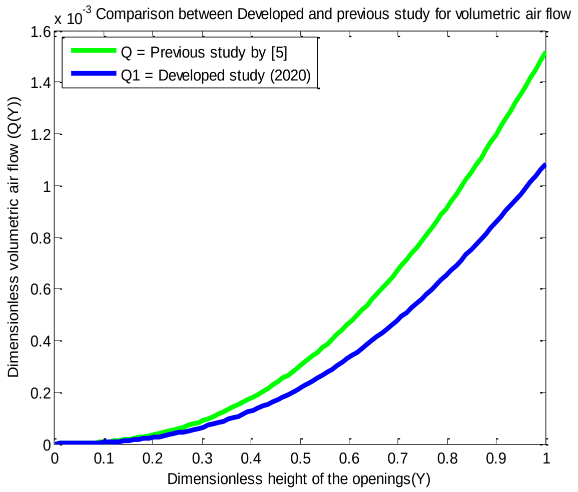

Fig. 16 Comparison between volumetric airflow Q and $Q1$ for fixed values of

$\theta_0 = 0.3, Pr = 0.710, C_d = 0.60$ and $Gr = 2.0$

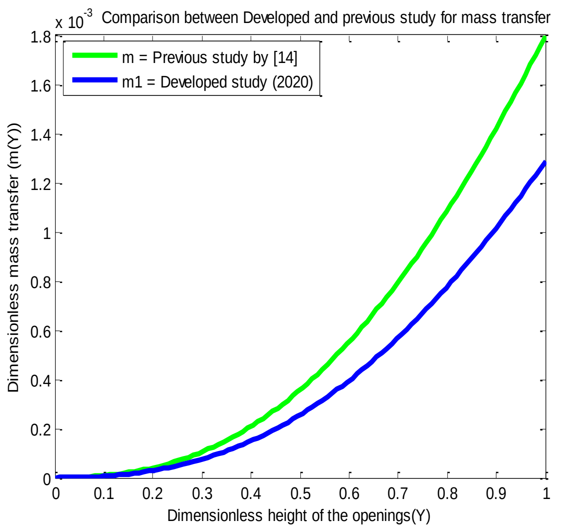

Fig. 17 Comparison between mass transfer m and $m1$ for fixed values of $\theta_0 = 0.3, Pr = 0.71, C_d = 0.6$ and $Gr = 2.0$

Fig. 3 reveal the influence of effective thermal coefficient (θ_0) on the airflow temperature distributions across the openings. It is clearly seen that airflow temperature increase with the increase of effective thermal coefficient (θ_0).
Fig. 4, 5 and 6 reveal the influence of effective thermal coefficient (θ_0), Prandtl number (Pr) and Grashof number (Gr) (is a non- dimensional group which approximate the ratio of the buoyancy to viscous force acting on a fluid), on the airflow velocity distributions across the openings. It is clearly seen that airflow velocity increase with the decrease of effective thermal coefficient (θ_0) and Prandtl number (Pr) and airflow velocity increase with the increase of Grashof number (Gr). This is physically true since growing Prandtl number decreases thermal diffusivity of the air.
Fig. 7, 8, 9 and 10 reveal the influence of effective thermal coefficient (θ_0), Prandtl number (Pr),Grashof number $(Gr)$and discharge coefficient (C_d)on the volumetric airflow in the building. can be discovered that volumetric airflow goes significantly upward with the decrease of effective thermal coefficient (θ_0) and Prandtl number (Pr) while, volumetric airflow goes significantly upward with the increase of discharge coefficient (C_d) and Grashof number (Gr).
Fig. 11, 12, 13 and 14 reveal the influence of effective thermal coefficient (θ_0), Prandtl number (Pr), Grashof number (Gr) and discharge coefficient (C_d)on the mass- transfer. It can be discovered that mass- transfer goes significantly upward with the decrease of effective thermal coefficient (θ_0) and Prandtl number (Pr) and mass transfer goes significantly upward with the increase of Grashof number (Gr) and discharge coefficient (C_d).
Fig. 15, 16 and 17 shows the comparison between present and the previous work by [5]. The main contributions from the present work is that, effect of changes of parameters involved in the results goes significantly upward compared with the previous work. Therefore, effective thermal coefficient (θ_0), Prandtl number (Pr), Grashof number (Gr) and discharge coefficient (C_d) exerts significant influence on the air flow velocity across the openings in the building envelope.

V. CONCLUSIONS

The paper studied the convective air flow process in rectangular building with Four upper vents induced by stack- driven effect. The governing equations describing the flow are written in dimensionless form and solved theoretically by means of Laplace transform and variation of parameter method. The effect of each physical parameter involved in the study are discussed with aid of graphs. It was found that effective thermal coefficient (θ_0), Prandtl number (Pr) and Grashof number (Gr) exerts significant influence on the velocity, temperature distributions together with mass- transfer and volumetric airflow.
The following major conclusions have been achieved from the paper.

1- Temperature increase with an decrease of effective thermal coefficient (θ_0).
2- Velocity distributions across the openings decrease with an increase of effective thermal coefficient (θ_0) and Prandtl number(Pr)while, velocity distributions across the openings increase with an increase of Grashof number (Gr).
3- Volumetric airflow increase with an decrease of effective thermal coefficient(θ_0) and Prandtl number (Pr) while, volumetric airflow increase with an increase ofGrashof number (Gr) and discharge coefficient (C_d).
4- Mass- transfer increase with an increase of effective thermal coefficient (θ_0) and Prandtl number (Pr)while, mass transfer increase with an increase of Grashof number (Gr) and discharge coefficient (C_d).
5- In the present results, velocity distributions across the opening goes significantly upward compared with the results given by [5]

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