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# Numerical Study of Forced Convective Heat Transfer on Horizontal Flat Plate

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## Abstract
In this study, numerical estimations of local Nusselt number along flat plate are examined. ANSYS CFD software was used to construct, solve and present problem. Two types of convective heat transfer simulations were carried out namely, laminar and turbulent flow over an isothermal plate and laminar and turbulent flow over plate at constant heat flux. A CFD model was adopted to simulate convection in air, $CO_2$ and water vapor. The boundary-layer thickness was used for laminar and turbulent 2 cm and 3.4 cm respectively. The results showed that the local Nusselt number differed by 1.03 % for laminar flow and 4.44 % for turbulent flow from published data for isothermal plate simulations, as for constant heat flux simulations the local Nusselt number differed from published data by 1.84 % for laminar flow, and 5.5 % for turbulent flow. The result also tells us that the boundary-layer thickness for laminar and turbulent flow increase with distance from the leading edge of the flat plate. The results were in very good agreement with the published data for correlation equation of local Nusselt number.

**Keywords**: correlation equation, isothermal plate, constant heat flux, laminar & turbulent flow.


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# دراسة انتقال الحرارة بالحمل القسري نظرياً فوق صفيحة مسطحة افقياً

**أ. علي علي الخربوشي، أ. إيهاب أبو العيد بركة**
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**الملخص**

تم نظرياً دراسة عدد نسلت فوق صفيحة مسطحة باستخدام برنامج انسس. وتم اختبار انتقال الحراري القسري في حالتي ثبوت درجة الحرارة وثبوت معدل تدفق الحرارة مع اخذ بعين الاعتبار اختلاف شكلي التدفق مرة تدفق طبقي ومرة أخرى تدفق مضطرب. الموائع التي تم استخدامها في هذه الدراسة هي الهواء، ثاني أكسيد الكربون وبخار الماء، كما ان سماكة الطبقة الحدية المستخدمة في هذه الدراسة 2 سم للتدفق الطبقي و 3.4 سم للتدفق المضطرب.

وقد تم مقارنة هذه النتائج بالنتائج المتحصل عليها من الدراسات السابقة وأظهرت هذه المقارنات وجود تشابه كبير بين النتائج بحيث كانت نسبة الخطأ لا تتجاوز 1.03 % للتدفق الطبقي و4.44 % للتدفق المضطرب في حالة ثبوت درجة الحرارة، أما في حالة ثبوت معدل تدفق الحرارة فإن نسبة الخطأ كانت 1.84 % للتدفق الطبقي و5.5 % للتدفق المضطرب. كما أظهرت النتائج زيادة سماكة الطبقة الحرارة الحدية مع زيادة المسافة من حافة الصفيحة. بشكل عام أظهرت المقارنات توافق عالي بين النتائج الحالية والنتائج السابقة.

## 1. Introduction

Heat transfer is defined as a science that aims to calculate the amount of heat transferred from one region to another as a result of temperature difference between them. The rate and how the heat is transferred varies according to the properties of the materials it passes through. Heat transfer can take place under two different thermal boundary conditions. Firstly, uniform heats flux boundary condition, which is generally applied to a practical situation of electric resistance heating and nuclear applications. Secondly, a


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uniform wall temperature boundary, which is approached when the outer-tube surface of a heat exchanger is heated by an isothermally condensing fluid or likewise cooled by an isothermally boiling fluid [1].

External forced convection is the most important part in applications of engineering. It requires either that the fluid be pumped past the body, as for a model in a wind tunnel, or the body be propelled through the fluid, as an aircraft in the atmosphere. The methods presented apply equally to either situation when velocities are expressed relative to the body. Gravity forces are usually negligible under these conditions. The evaluation of forced convection to bodies has become a major problem many aspects of modern technology. A few examples of applications include thermally de-icing aircraft surfaces, turbine blade cooling, furnace tube bundles, and protecting high-performance aircraft, missile nose cones, and reentry bodies from intense aerodynamic heating [2].

This paper deals with highlights of a recent research that seeks for forced convective heat transfer of different fluids over horizontal flat plat based on CFD analysis. The parameters that are considered: different fluids (air, $CO_2$ and water vapor), the type of flow (laminar and turbulent) and convective heat transfer conditions (isothermal plate and constant heat flux). The simulation was use in finding correlation equation for calculating convective heat transfer coefficients, and comparing the obtained results to published data.

## 2. Numerical Modeling

### 2.1. Geometrical Model

As it was mentioned, this paper covers highlights of the numerical study (CFD simulations) of what it has been done in the research. The geometry chosen for this simulation is shown in Figure(1.a and b) for laminar and turbulent flow, respectively. The figures show the dimensions of the domains and their boundary labels which will be used to set the boundary conditions. The height of the domain is based on the boundary layer thickness.


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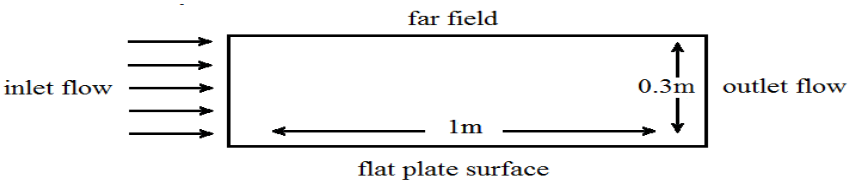
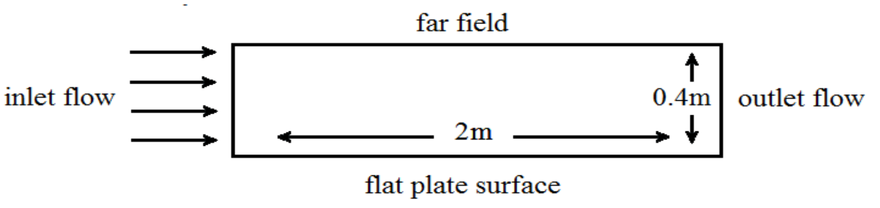



(a)




(b)

Figure 1. (a) The domain of laminar flow, (b) The domain of turbulent flow

**2.2. Boundary Conditions, Assumptions and Governing Equations**

The boundary conditions used when solving the problem are:

1- The inlet velocity at the left side.
2- The outlet pressure at the right side.
3- In viscid wall with a constant temperature at the top.
4- Constant temperature or constant heat flux at the bottom.

The properties that changed to calculate Correlation equation of Nusselt number are shown in Table 1 & Table 2 for isothermal surface and Table 3 for constant wall heat flux.

**2.2.1. Isothermal Surface Condition**. The properties that used in isothermal surface condition based on type of flow were shown in Table 1 for laminar flow and Table 2 for turbulent flow.


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**Table 1Gases properties of isothermal surface in laminar flow**

| No. | Gas | $T_f$ (K) | $\rho$ (kg/m$^3$) | $c_p$ (J/kg.K) | k.10$^3$ (W/m.K) | $\mu$.10$^5$ (N.s/m$^2$) | U (m/s) | Pr |
|---|---|---|---|---|---|---|---|---|
| 1 | air | 436.5 | 0.800 | 1019.1 | 36.355 | 2.4513 | 5<br>15 | 0.6870 |
| 2 | air | 486.5 | 0.650 | 1037.3 | 43.036 | 2.8345 | 4<br>16 | 0.6832 |
| 3 | $CO_2$ | 436.5 | 1.218 | 970.47 | 27.22 | 2.046 | 5<br>8 | 0.7304 |
| 4 | $CO_2$ | 536.5 | 0.989 | 1041.9 | 35.201 | 2.456 | 3<br>12 | 0.7220 |
| 5 | Water vapor | 436.5 | 0.507 | 1989.1 | 28.802 | 1.4761 | 5<br>14 | 1.0181 |
| 6 | Water vapor | 536.5 | 0.411 | 1993.7 | 45.078 | 1.8354 | 3<br>21 | 0.9943 |

**Table 2Gases properties of isothermal surface in turbulent flow**

| No. | Gas | $T_f$ (K) | $\rho$ (kg/m$^3$) | $c_p$ (J/kg.K) | k.10$^3$ (W/m.K) | $\mu$.10$^5$ (N.s/m$^2$) | U (m/s) | Pr |
|---|---|---|---|---|---|---|---|---|
| 1 | air | 425 | 0.823 | 1017.5 | 35.55 | 2.404 | 80<br>100 | 0.688 |
| 2 | air | 475 | 0.735 | 1025.5 | 39 | 2.604 | 95<br>110 | 0.685 |
| 3 | $CO_2$ | 440 | 1.207 | 973.2 | 27.5 | 2.06 | 50<br>70 | 0.7298 |
| 4 | $CO_2$ | 550 | 1.178 | 981 | 28.3 | 2.1 | 70<br>110 | 0.728 |
| 5 | Water vapor | 450 | 0.490 | 1980 | 30.8 | 1.525 | 80<br>100 | 1.01 |
| 6 | Water vapor | 500 | 0.4405 | 1985 | 38.68 | 1.704 | 100<br>110 | 0.998 |

**2.2.2. Constant Wall Heat Flux**. The properties that used for constant wall heat flux condition in both types of flow laminar and turbulent flow shown in Table 3. It should be mentioned that the inviscid wall has the same temperature as the inlet temperature.


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**Table 3 Gases properties of constant wall heat flux**

| No. | Gas | $T_f$ (K) | $\rho$ (kg/m$^3$) | $c_p$ (J/kg.K) | $k.10^3$ (W/m.K) | $\mu.10^5$ (N.s/m$^2$) | U (m/s) Lami. | U (m/s) Turb. | Pr |
|---|---|---|---|---|---|---|---|---|---|
| 1 | air | 400 | **0.871** | 1014 | 33.8 | 2.301 | 5 | 70 | **0.69** |
| | | | | | | | 12 | 100 | |
| 2 | air | **450** | **0.774** | **1021** | **37.3** | 2.507 | 5 | **85** | 0.686 |
| | | | | | | | 15 | **100** | |
| 3 | $CO_2$ | 400 | **1.325** | 942 | 24.3 | 1.9 | 5 | 40 | 0.737 |
| | | | | | | | 7 | 60 | |
| 4 | $CO_2$ | 500 | **1.059** | 1020 | 32.5 | 2.31 | 5 | 60 | **0.725** |
| | | | | | | | 10 | 80 | |
| 5 | Water vapor | 400 | **0.554** | 2014 | 26.1 | 1.344 | 5 | 70 | 1.04 |
| | | | | | | | 10 | 100 | |
| 6 | Water vapor | **450** | 0.490 | 1980 | 29.9 | 1.525 | 5 | 85 | 0.998 |
| | | | | | | | 18 | 100 | |

## 2.3. Multiple Regression Analysis

It is a statistical tool that allows examining how multiple independent variables are related to a dependent variable. Once identified how these multiple variables relate to your dependent variable, the information about all of the independent variables can be taken and use it to make much more powerful and accurate predictions. Using Microsoft excel [3].

## 2.4. Used Equations

The basic equations that used in this work as Nusselt number equations of published data boundary layer thickness are mentioned in Table 4.

**Table 1 Basic equations of convective heat transfer**

| Name | Equation | Flow Type |
|---|---|---|
| Isothermal surface | $Nu = 0.332 \times Re^{\frac{1}{2}} \times Pr^{\frac{1}{3}}$ | laminar |
| Isothermal surface | $Nu = 0.0296 \times Re^{\frac{4}{5}} \times Pr^{\frac{1}{3}}$ | turbulent |
| Constant wall heat flux | $Nu = 0.453 \times Re^{\frac{1}{2}} \times Pr^{\frac{1}{3}}$ | laminar |


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| | | |
|---|---|---|
| Constant wall heat flux | $Nu = 0.0308 \times Re^{\frac{4}{5}} \times Pr^{\frac{1}{3}}$ | turbulent |
| Boundary layer thickness | $\delta = 5 \times x/(Re)^{\frac{1}{2}}$ | laminar |
| Boundary layer thickness | $\delta = 0.37 \times x/(Re)^{\frac{1}{5}}$ | turbulent |

Several important assumptions are considered in this study and some of them are also used as boundary conditions for the CFD analysis. These assumptions are:

- Incompressible flow.
- The flow is steady state and in two dimensional.
- Gravity acceleration neglected.
- Since the water velocity is low, therefore the viscous dissipation effect is neglected.
- The heat transfer radiation is neglected.
- The flat plate surface is assumed to be a stationary wall with no slip condition.
- All Gas material properties are constant.

The processing step of computational fluid dynamics consists of several main principles as basic for solving fluid flow and heat transfer problems. Those principles are the principle of conservation of mass, the Newton's Second Law of Motion, the principle of First Law of Thermodynamics, and several related physical models, such as ideal gas model, turbulence models, etc.

Those principles are implemented into equations such as the continuity equation, the linear momentum equation, and the energy equation known as governing equations. Those governing equations are used simultaneously by the CFD to find the desired solution (i.e. temperature, velocity or pressure contour) of the fluid flow and heat transfer problems by using a numerical method [4].

Basically the governing equations consist of continuity equation, momentum equation, energy equation implemented in the Ansys Fluent 15.0. These equations can be expressed as following [5], [6].


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**1.Continuity Equation**. The continuity equation, or equation for conservation of mass, can be written in the tensor notation as follows:

$$\nabla.\rho\vec{V} = 0 \qquad (1)$$

Where: $\rho$ is the fluid mass density and $\vec{V}$ fluid velocity vector.

**2. Momentum Equation**. Conservation of momentum in an inertial (non-accelerating) reference frame can be described by the following equation:

$$\nabla.\left(\rho\vec{V}\vec{V}\right) = -\nabla p + \nabla.\vec{\tau} + \rho\vec{g} \qquad (2)$$

Where: $p$ is the static pressure, $\vec{\tau}$is the stress tensor (described below), and $\rho\vec{g}$is the gravitational body force.

The stress tensor can be expressed as following:

$$\vec{\tau} = -\mu\left[\left(\nabla\vec{V} + \vec{V}^T\right) - \frac{2}{3}\nabla.\vec{V}\vec{I}\right] \qquad (3)$$

Where: $\mu$ is the molecular viscosity, $\vec{I}$ is the unit tensor, and the second term on the right hand side of equation (3) represents the effect of volume dilation.

**3. Energy equation**. The energy conservation equation can be expressed in the following form:

$$\nabla.\left[\vec{V}\rho\left(h + \frac{1}{2}v^2\right)\right] = \nabla.(k\nabla T) \qquad (4)$$

Where: $k$ is the thermal conductivity of the fluid, and $T$ is temperature of the fluid.

## 3. Results and discussion

### 3.1 Effects of Velocity at Isothermal Surface

Figure 2.a shows the influence of fluid velocity on Nusselt number for isothermal surface at laminar flow. From the figure can be seen that Nusselt number will be increased with increasing of flow velocity over flat plat. This is because by increasing velocity of fluid, the flow rate will be increasing, therefore it will be more fluid available over flat plate, to absorb the heat transferred from the surface.


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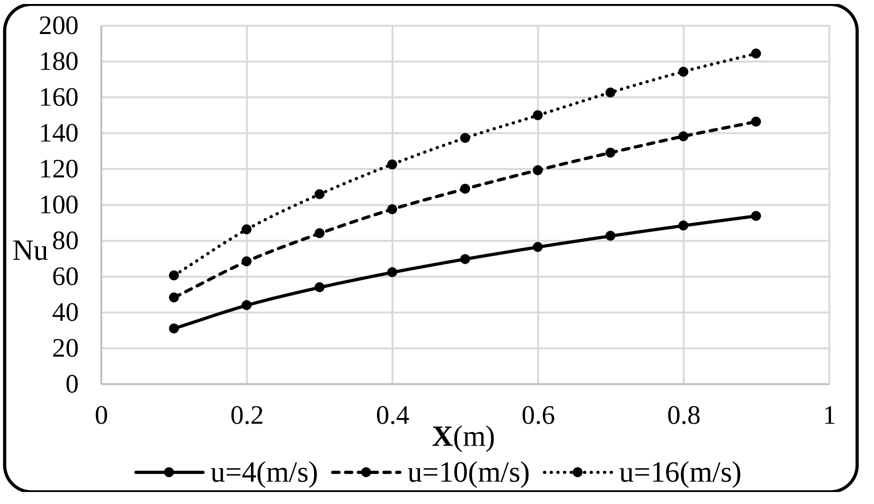
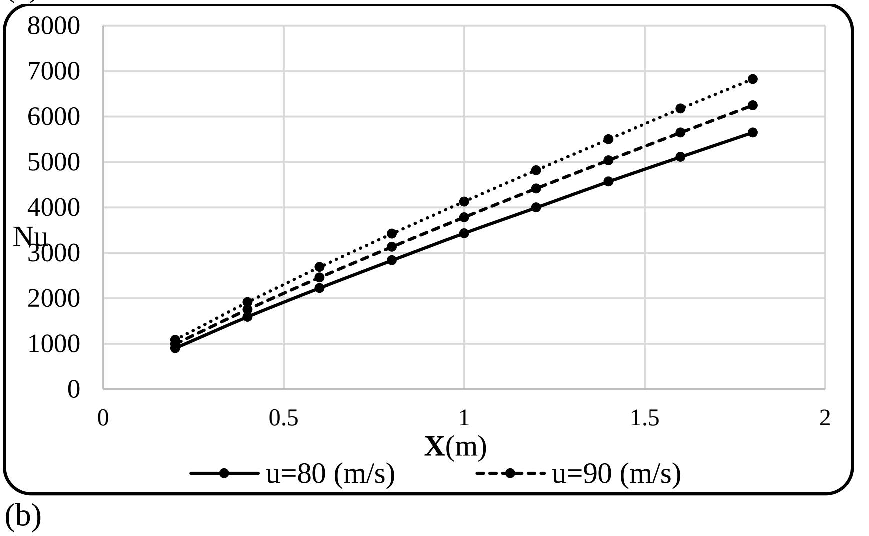



(a)




(b)

Figure 2. Effect of velocity on Nusselt number.
(a) laminar flow at $T_s$ = 573 K, (b) turbulent flow at $T_s$ = 550 K

Figure 2.b shows the effect of the velocity of working fluid (air) on Nusselt number for a surface with isothermal surface at turbulent flow. It can be seen from the figure that Nusselt number will be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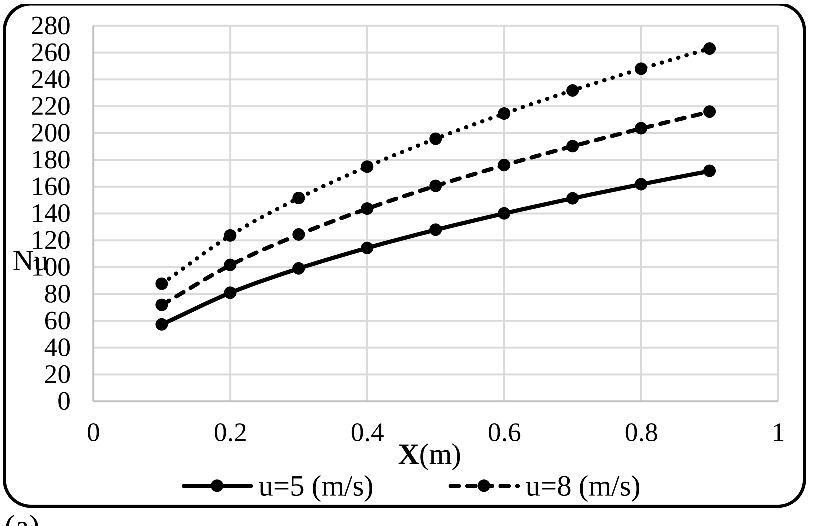
increased with increasing of flow velocity over flat plat. This phenomenon happened because of the same reasons were explained in section 3.1.

### 3.2 Effects of Velocity at Constant Heat Flux

Since, there is no much difference in behavior of other gases that has been chosen as working fluids in this project. Thus, the air was chosen as the fluid material to study the effect of fluid velocity on forced convective heat transfer over the plate.
The influence of fluid velocity on Nusselt number for a surface with constant heat flux at laminar flow is shown in Figure 3.a. It can be seen that Nusselt number will be increased with increasing of flow velocity over flat plat. This is because by increasing velocity of fluid.
Figure 3.b shows the influence of the velocity of working fluid (air) on Nusselt number for a surface with constant heat flux at turbulent flow. Nusselt number will be increased with increasing of flow velocity.



(a)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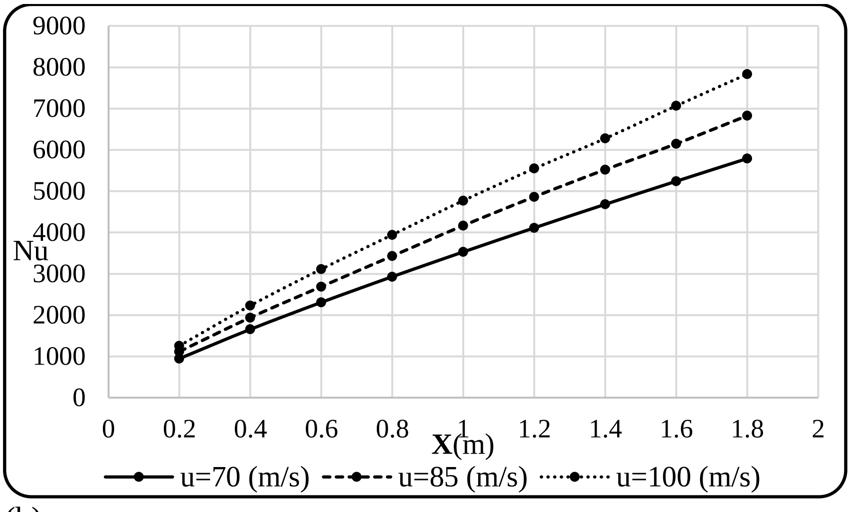

(b)

Figure 3. Effect of velocity on Nusselt number.
(a) laminar flow at q"=2.5 kW/m$^2$, (b) turbulent flow at q"=10 kW/m$^2$

### 3.3 Effect of Fluids Properties on Forced Convection

To study the effect of different fluids on forced convective heat transfer over horizontal flat plate air, carbon dioxide and water vapor were chosen as the fluid material. The case of laminar flow for isothermal surface was selected to illustrate this effectiveness.
Figure 4 shows the effect of the rmophysical properties for different gases on Nusselt number. These gases were flowed over flat plate at velocity inlet of 5 m/s. The surface temperature was 573 K. as can be seen from the figure, the Nusselt number of $CO_2$ was highest value and then water vapor and the air, respectively. This trend due to the difference in properties for each fluid, in addition to this reason, it should be noted that the direct effect of Nusselt number by thermal conductivity of each fluid gives logical interpretation of what has be seen in the figure.

It can be seen that as increasing in thermal conductivity of the fluid, Nusselt number is decreased. The thermal conductivity of the air is higher than the thermal conductivity of water vapor and $CO_2$, respectively.


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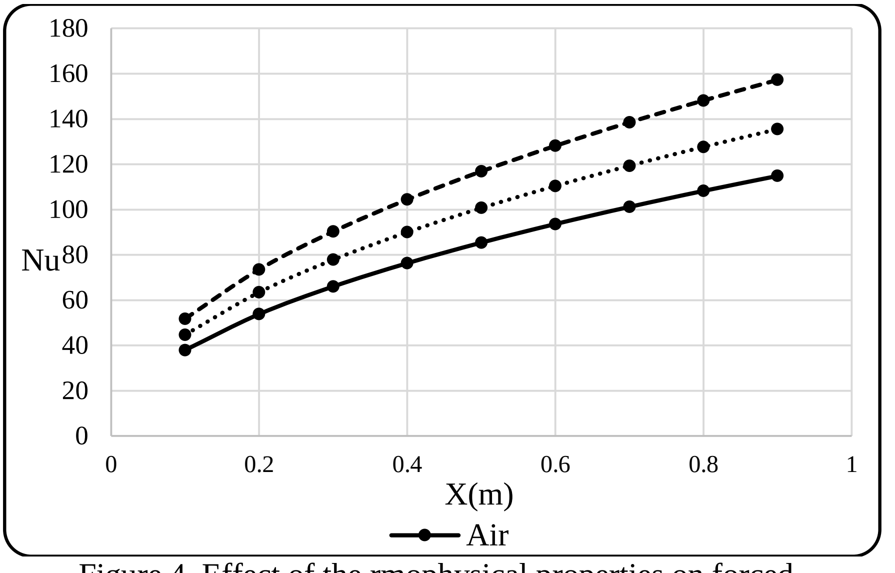


Figure 4. Effect of the rmophysical properties on forced convection

### 3.4 ForcedConvection CorrelationEquation

In forced convection, a variety of correlations are in use to predict rates of convection in laminar and turbulent flow. As mentioned in before, Nusselt number is the ratio of thermal transfer between convection and conduction.

The Nusselt number for a given geometry can be expressed in terms of the Reynolds number (Re), the Prandtl number (Pr), and such a relation can be used for different fluids flowing at different velocities over similar geometries of different lengths, the correlation for Nusselt number appears as in the Equation 5 [1].

$$Nu = \mathrm{C}.Re^{n}.Pr^{m} \quad (5)$$

Where: *m* and *n*: Constant exponents (usually between 0 and 1)
C: Constant value depends on the geometry


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**Table 5.Coefficients for the forced convective correlation equation**

| Thermal condition | C | n | m | Flow type |
|---|---|---|---|---|
| Constant heat flux | 0.4310 | 0.505 | 0.283 | Laminar |
| | 0.0206 | 0.831 | 0.638 | Turbulent |
| Isothermal surface | 0.3290 | 0.501 | 0.290 | Laminar |
| | 0.0163 | 0.840 | 0.520 | Turbulent |

After many results were taken at different temperatures and velocities, the results were compiled through multiple regression function. The coefficients for the forced convective correlation equation of local Nusselt number of this study was inserted in Table 5.

## 4. Closing Remarks

A numerical simulation study on forced convection heat transfer characteristics of different gases flow over horizontal flat plate geometry under steady state flow has been conducted in this study. The study was done to satisfy the correlation equation in both cases of forced convective at isothermal surface and constant wall heat flux. The correlation equations show similar trends and relatively in good agreement with published theoretical data.

## 5. References

[1] Y. A. Cengel, Heat Transfer, Troy, Michigan, United States: McGraw-Hill, 2002.

[2] T. l. Bergman, A. s. Lavine, F. p. Incropera, D. p. Dewitt, Introduction to Heat Transfer, Jefferson, Missouri, United States: John Wiley & Sons, 2011.

[3] J. Higgins, "Introduction to Multiple Regression," in The Radical Statistician, Folsom, California, United States, Biddle Consulting Group, 2005, pp. 1-15.


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[4] B. R. Munson, D. F. Young, T. H. Okiishi, W.H. Huebsch, Fundamental of Fluid Mechanic 4th Edition, J. Wiley & Sons, 2002.

[5] E. Britannica, "Flow Physics," Encyclopædia Britannica, 1 1 2017. [Online]. Available: https://www.britannica.com/science/laminar-flow. [Accessed 1 4 2017].

[6] N. Boskovic, "Ansys Fluent Users Guide," 1 11 2011. [Online]. Available: https://www.scribd.com/doc/140163383/Ansys-Fluent-14-0-Users-Guide. [Accessed 1 5 2017].


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