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Experimental study of the external forced convection heat transfer of flat plate

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Abstract : An experiment was carried out in order to find the heat transfer coefficient of a flat plate in the process of cooling by forced convection, the plate has four thermocouples located at equal distance along this one, it was evidenced the change of the coefficient of heat transfer according to the position of the plate, and the non-dimensional parameters such as the Reynolds, Nusselt and Prandtl number were found, and the experimentally found data and the software data were compared.
Keywords: External forced convection, heat transfer.

Introduction

At present, the teaching-learning process in higher education institutions is based on the development of master classes, which promote student self-learning as a complementary aspect of the vocational training process [1]. In engineering education, practical experience is very important to study and understand the theoretical foundations treated in a class, since students show interest and motivation when developing practical skills in the laboratory, facilitating the assimilation and conceptual appropriation [2,3].

In developing the laboratory experiences in the different academic programs, they depend on both the laboratory equipment and the spaces available in the university that allow to guarantee the fulfillment of the curriculum, in this way, it is justified that the students have in their training process a learning experience to design and perform oriented to solve real problem situations [4]. In order to train students with critical, scientific and reflexive thinking, experimentation is a means to obtain global knowledge, which can be achieved through the development and construction of laboratory equipment. In addition, it is important for students to carry out activities that help them to think for themselves, and to feel an active part of the training process, which, in case of being interactive through the use of technological tools, guarantees successful results [5].

Taking into account that a high percentage of students entering university require educational strategies to arouse their interest in the classes that allow them to increase their academic performance, it is necessary to generate spaces in the different subjects for the study of the phenomena of a didactic and reliable way [6]. Many educational institutions have implemented the European Higher Education Area (EHEA) model based on autonomous student learning, in which the practical experience has been increased to 6.34%, which improves or increases the chances of future employability to 8.27% [7], demonstrating that the improvement of the quality of education impacts the success of the professional, generating appropriate environments for the production and transfer of knowledge, since competences are developed that are linked to the labor market [8].

In order to promote learning, a group of students of Engineering carried out an experimental study on the phenomenon of heat transfer by forced convection, taking into account the wide application of this principle in real situations and projects such as building construction, where the evaluation of heat transfer processes is essential to identify the performance of the structural elements. In this case the students studied the heat transfer that occurs in internal and external environments between walls and surrounding bodies, being quantified by the convective coefficient and radiation [9,10]. Likewise, experiments have been performed not for real situations, but rather to better understand the subjects seen in class as the realization of an experiment performed by the students to determine the coefficient of heat transfer by relating the Nusselt number and the Reynolds number and other topics [11,12].

The main objective of this work is to experimentally study the external forced convection heat transfer [13], developing a prototype for the study of this subject, taking into account what has been learned in the courses of design of equipment and processes and heat transfer, in order to obtain the coefficient of heat transfer according to the position of a flat plate in the process of forced air cooling. A low-cost experiment is proposed, giving the student the opportunity to take part in the construction of the experiment, with its respective data acquisition and processing system with the Arduino card and its validation with analytical results.

Methodology

Equipment Description

The test bench as shown in the **Error! Reference source not found.**, allows the experimental study of the behavior of heat transfer by forced external convection. This equipment developed by the students consists of a housing (1) that serves as a duct due to its cylindrical geometry, made of polyvinyl chloride (PVC) of diameter 4", thickness of 0.2cm and a length of 100cm, which at one end it is free to the environment allowing the exit of the air flow of the system. The other end of the housing has a cover of this same material, coupled with a fan (2) operating at a voltage of 12v and a current of 0.62A, allowing experiments at different speeds through the installed potentiometer.

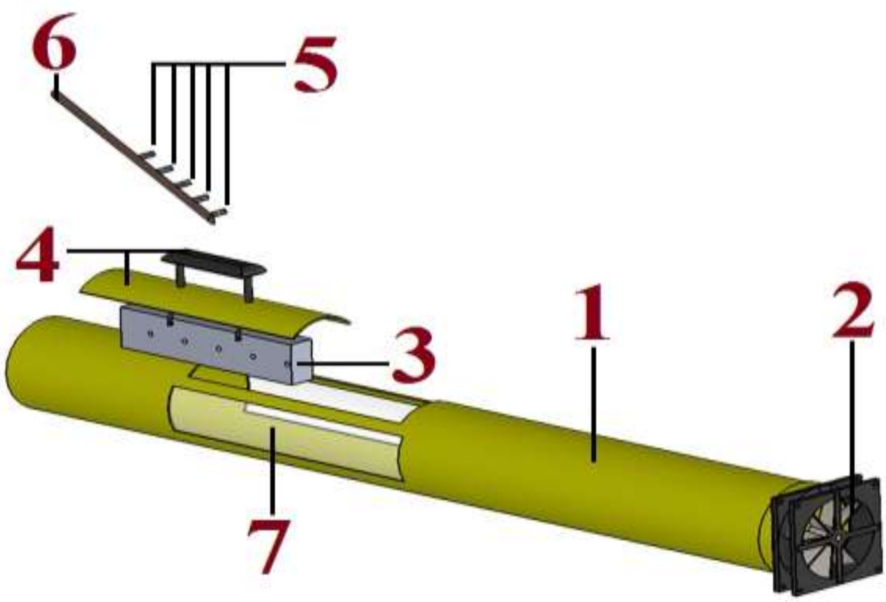


Figure 1. Experimental Equipment Setup. 1. Shield 2. Fan 3. Study piece 4. Gate 5. Thermometers 6. Cabling

In the upper part of the housing at a distance of 45cm from the fan, an upper hatch (4) of an area of 28cm in length and 7cm in width is placed to allow the study piece (3) to enter; the gate consists of a clamping mechanism for easy opening. This piece is of an alloy 61S of measures 20x5x2,5cm^3, its main elements of composition are aluminum, magnesium and silicon [14,15]; which was machined for the installation of the four temperature sensors (5) type K, which support high temperatures[16,17].

For the data collection and the adequate development of the experiment, jumpers cables (6) are used to achieve a connection between the electronic components, four MAX6675 cards which perform the compensation and linearization of the response of the sensor (Thermocouples) with an ADC, with a resolution of 0.25º and range of use of the card between 3.0V to 5.5V [18]. Finally, an Arduino UNO microcontroller is used to obtain the data of these cards and to digitize in the computer by means of the software Arduino[19].

Fundamental Equations

Considering the laminar flow of a fluid on a flat plate, the fluid approaches in the x direction with a uniform velocity upstream, which is equivalent to the velocity V of the free stream as seen in the **Error! Reference source not found.**[20].

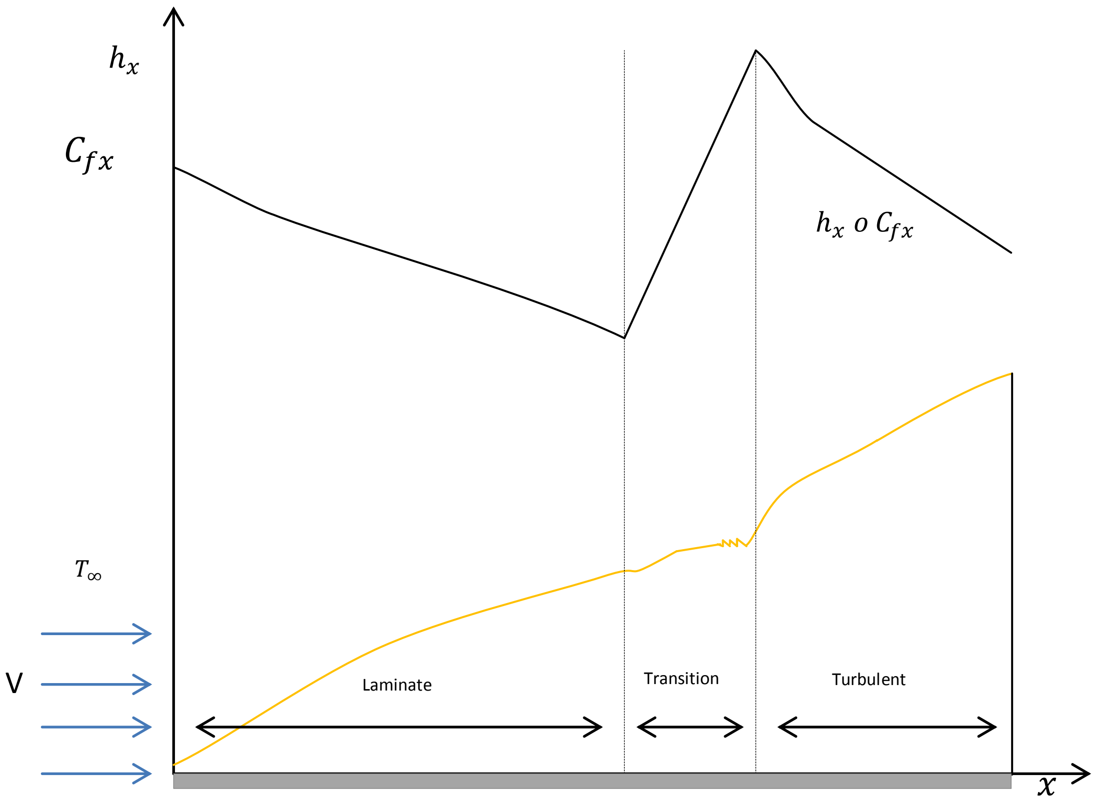


Figure 2.Representation of the heat transfer coefficient in turbulent and laminar regime

To obtain the coefficient of heat transfer in a flat plate, it must solve the following equation of convection of the energy on a flat plate

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}= \alpha\frac{\partial^2 T}{\partial y^2}. \quad (1)$$

If you have a constant wall temperature T_S

$$\boldsymbol{\theta}(\boldsymbol{x},\boldsymbol{y}) = \frac{\boldsymbol{T}(\boldsymbol{x},\boldsymbol{y}) - \boldsymbol{T_S}}{\boldsymbol{T_\infty} - \boldsymbol{T_S}}, \quad (2)$$

ifT_∞ and T_S are constant is replaced in equation

Figure 2. Representation **of the heat transfer coefficient in turbulent and laminar regime**

To obtain the coefficient of heat transfer in a flat plate, it must solve the following equation of convection of the energy on a flat plate

$$\boldsymbol{u}\frac{\partial \boldsymbol{T}}{\partial \boldsymbol{x}} + \boldsymbol{v}\frac{\partial \boldsymbol{T}}{\partial \boldsymbol{y}} = \boldsymbol{\alpha}\frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{y}^2}. \quad (1)$$

$$\boldsymbol{u}\frac{\partial \boldsymbol{\theta}}{\partial \boldsymbol{x}} + \boldsymbol{v}\frac{\partial \boldsymbol{\theta}}{\partial \boldsymbol{y}} = \boldsymbol{\alpha}\frac{\partial^2 \boldsymbol{\theta}}{\partial \boldsymbol{y}^2}. \ (\mathbf{3})$$

The expressions for u and V are taking into account the temperature profiles, velocity profiles, the thickness of the thermal and velocity boundary layer. And by simplifying, for Pr> 0.6 it is found that the dimensionless temperature gradient on the surface is proportional to $\mathrm{Pr}^{1/3}$. The temperature gradient on the surface is expressed as

$$\left.\frac{\partial \boldsymbol{T}}{\partial \boldsymbol{y}}\right]_{\boldsymbol{y}=\mathbf{0}} = \mathbf{0.332}\boldsymbol{Pr}^{\frac{1}{3}}(\boldsymbol{T_\infty} - \boldsymbol{T_S})\sqrt{\frac{\boldsymbol{V}}{\boldsymbol{vx}}}. \quad (3)$$

Then, the local convection coefficient can be calculated as follows

$$\boldsymbol{h_x} = \frac{\dot{\boldsymbol{q}}_{\boldsymbol{s}}}{\boldsymbol{T_s} - \boldsymbol{T_\infty}} = \mathbf{0.332}\boldsymbol{Pr}^{\frac{1}{3}}(\boldsymbol{T_\infty} - \boldsymbol{T_S})\sqrt{\frac{\boldsymbol{V}}{\boldsymbol{vx}}}, \quad (4)$$

so the Nusselt number is estimated as

$$\mathrm{Nu_x} = \frac{\mathrm{h_x x}}{\mathrm{k}} = 0.332\mathrm{Re_x}^{0.5}\mathrm{Pr}^{1/3}, \quad (5)$$

$\mathrm{Pr} > 0.6$

where the Reynolds number at a distance x from the leading edge of a flat plate is,

$$\boldsymbol{Re_x} = \frac{\boldsymbol{\rho V x}}{\boldsymbol{\mu}} = \frac{\boldsymbol{Vx}}{\boldsymbol{v}}. \quad (6)$$

Also, the Reynolds number varies for a flat plate along the flow until it reaches $\mathrm{Re_L}$

$$\mathrm{Re_L} = \frac{\mathrm{VL}}{\mathrm{v}}. \quad (7)$$

To obtain the average Nusselt number on the entire plate, for laminar flow[21]

$$\mathrm{Nu} = \frac{\mathrm{hL}}{\mathrm{k}} = 0.664\mathrm{Re_L}^{0.5}\mathrm{Pr}^{1/3}, \quad (8)$$

Computational Simulation

The computational solution of this experiment was done by Flow Simulation in the program Solidworks[22]. The **Error! Reference source not found.**shows the computational domain and the boundary conditions, where the input temperature and pressure are specified in addition to a laminar flow intensity and the length. For the solid, non-slip boundary condition were applied, as well as a wall temperature specified, and a symmetric boundary condition was assumed in one side of the solid due to all variables have the same value and gradients at the same distance from the center. Finally, all the walls were considerate real and adiabatic.

Results and discussions

There are a variety of parameters, variables or factors that influence the determination of the heat transfer between a surface and a fluid, affecting the value of the heat transfer coefficient. The results allowed to verify the variation of the coefficient of heat transfer according to the position of a flat plate, where it is observed that the temperature is different in each point of the plate for the cooling process at different speeds, as shown for the experimental results in**Error! Reference source not found.**. As the distance of a point in the plate with respect to the air flow increases, the temperature will be higher because a local convective coefficient is lower and there is a lower temperature difference.

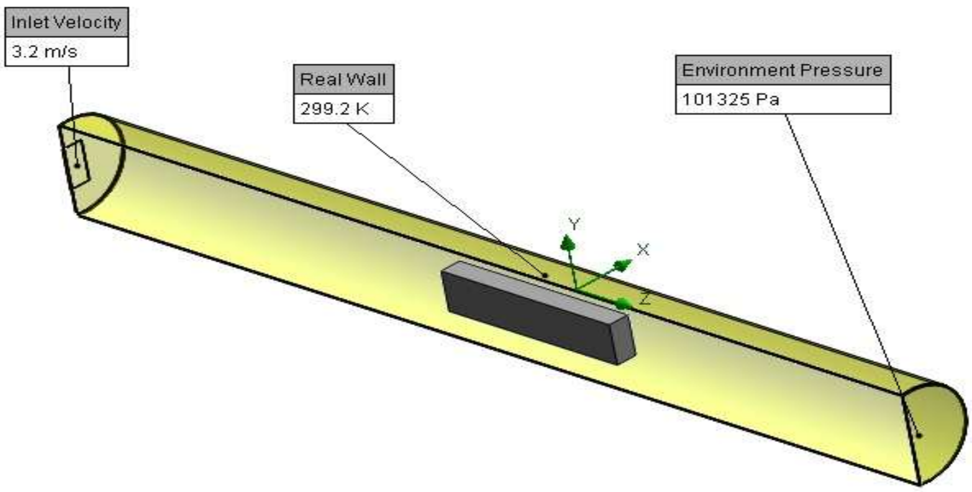
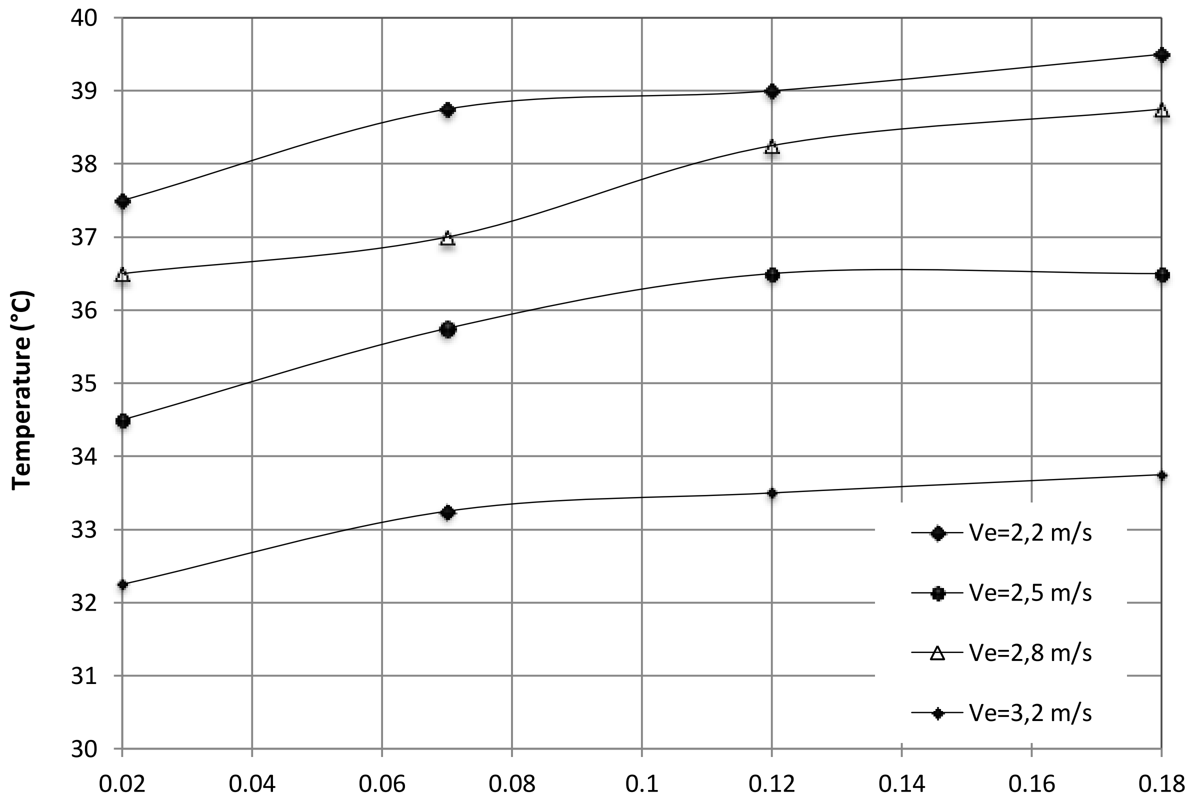


Figure 3.Computational domain



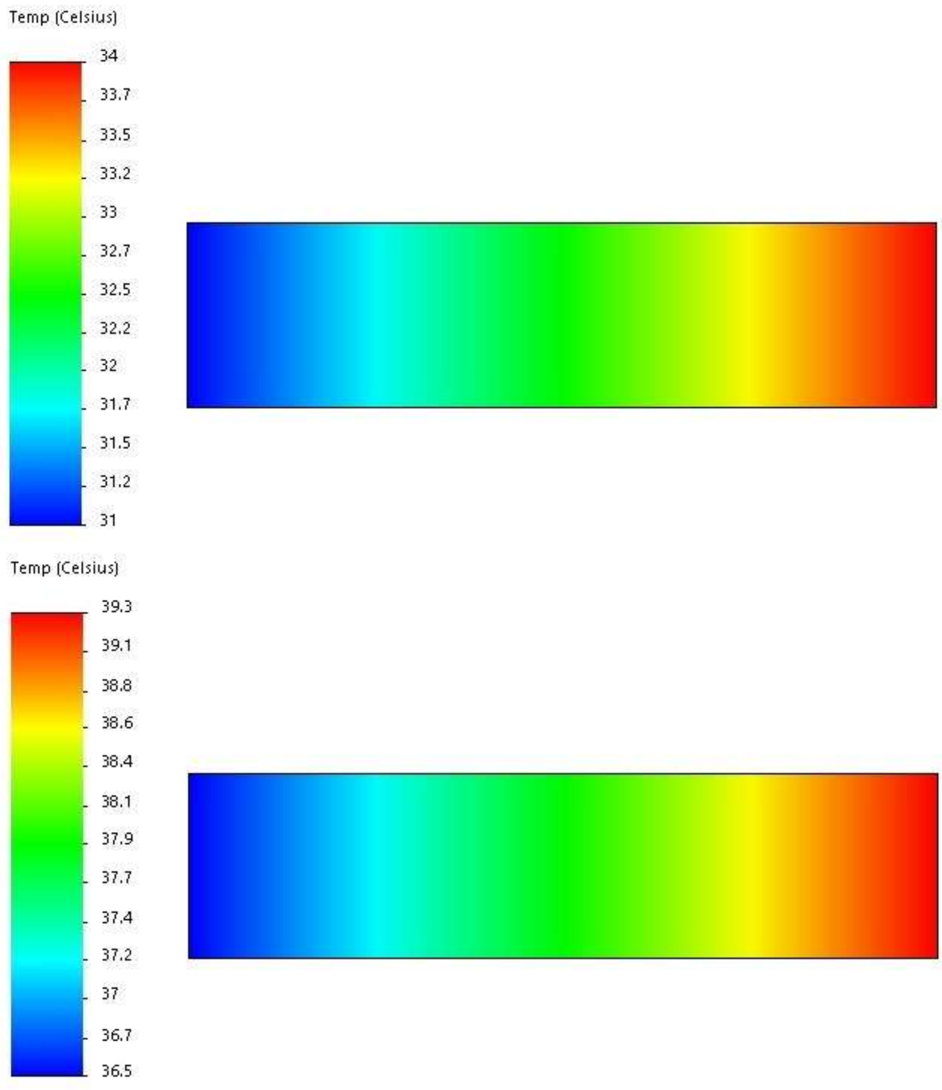


Figure 4.Profile Temperature

In order to perform a comparative analysis between the experimental results and the results of the computational simulation, a numerical study was made to the different flows, obtaining the temperature distributions of the solid and therefore the different convective coefficients in the simulation as is shown in**Error! Reference source not found.**.

Figure 5.Simulated temperatura field, a) Low Reynold Number, b) High Reynold Number

From the simulated and experimental results, a comparative analysis of the convective heat transfer coefficient was performed on the flat plate, as shown in **Error! Reference source not found.**, obtaining that for the velocity condition 3,2 m/s and position 0,18m has the biggest error 5,36%; While for the velocity condition 2,2 m/s and position 0,02 m we have the smallest error 0,68%, which shows that the design of the equipment, the planning and execution of the experimental tests were very well developed, and the assembly with its respective instrumentation can be used for the study of the phenomenon.

Likewise, in the case of the Nusselt number as shown in**Error! Reference source not found.**, in the cooling process of a flat plate for each point of the same plate, there will be a variation of the temperature, parameters and dimensionless numbers of the Process, as well as the characteristic length, which is the dominant parameter in this case, causing the Nusselt number to increase as a function of the position. When comparing the simulated data, it is observed that the average error presented is 2,05%, which shows that the Nusselt number can be calculated both experimentally and numerically with the assistance of computational fluid dynamics software.

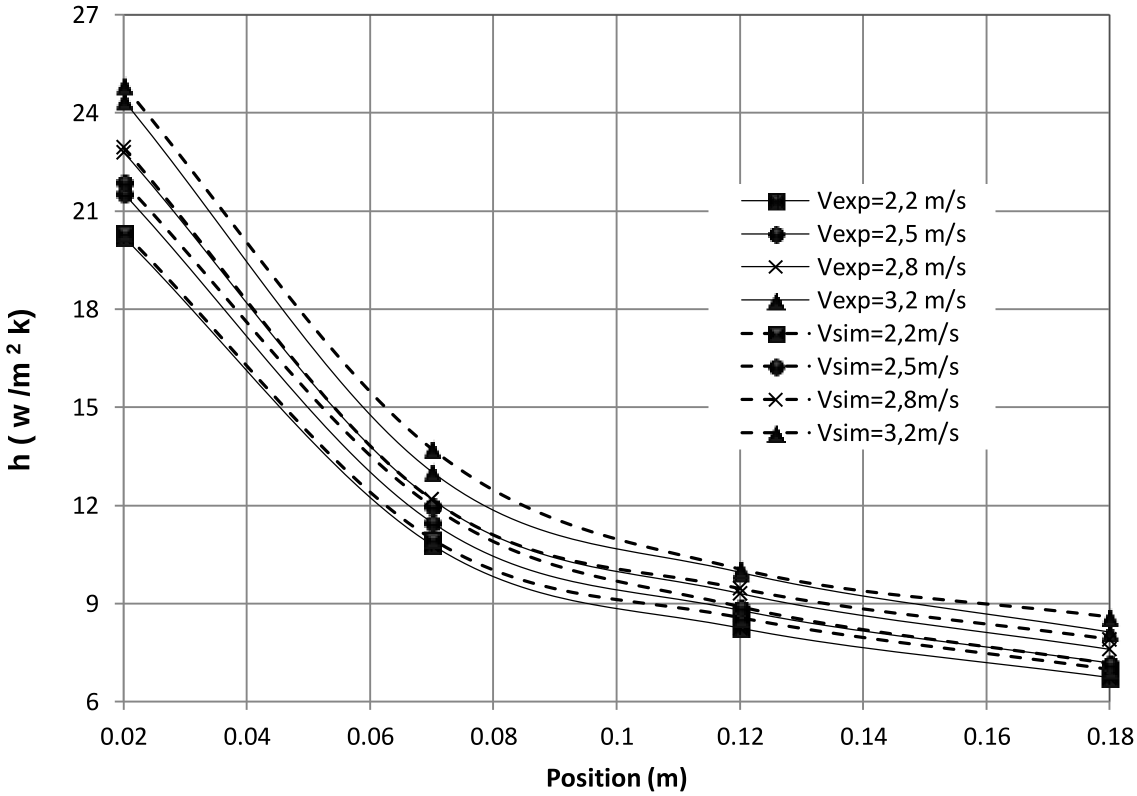


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Figure 6. Convective coefficient for experimental and computational results

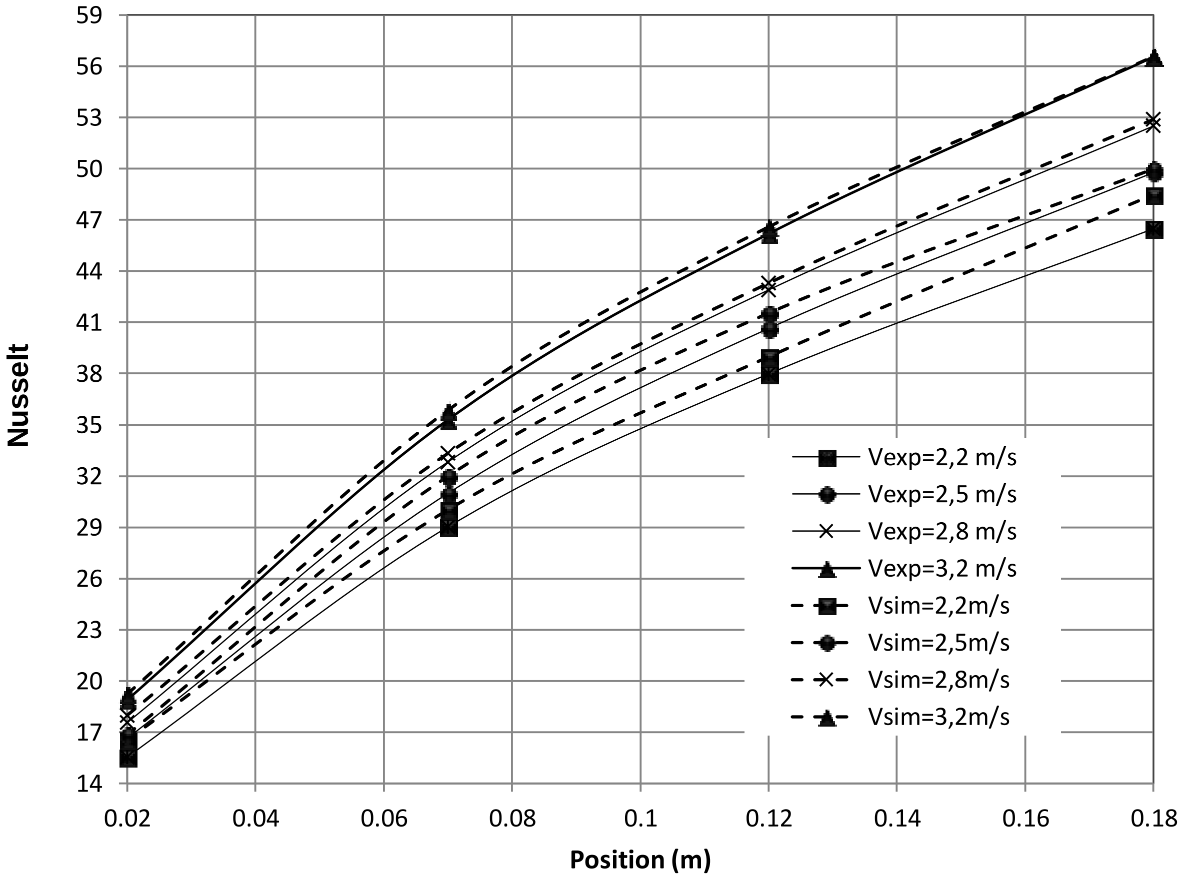

Figure 7. Nusselt number for experimental and computational results

Conclusions

The rationale and methodology presented in the heat transfer books to evaluate the convective coefficient h from the parameters and non-dimensional equations can be used to predict heat transfer coefficients in free and forced convection. These equations must be used because the factors that influence heat transfer are properties of the fluid and characteristics of the surface of the material so it will always be difficult to calculate the convection coefficient directly, as demonstrated in this study. It can be said that distance is an important factor when evaluating heat transfer and specifically the heat transfer coefficient, in turn there are formulas to predict the coefficient of heat transfer according to the position or distance of a flat plate.

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