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Experimental study of flat plate cooling using draft induced by a submerged radial jet

Estudio experimental del enfriamiento de una placa plana usando el tiro inducido de un jet radial

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ABSTRACT: An experimental research has been conducted for evaluating heat transfer in a modified configuration of a submerged radial jet, so it was possible to extract the fluid directly under the nozzle, looking for an improvement in the heat transfer rate. The experiments were conducted for the following ranges of the phenomenon governing parameters: 16 mm nozzle diameter, nozzle to plate distance ranging from 10 mm to 20 mm, Reynolds number ranging between 10,000 and 20,000, and heat density of 10.2 – 13.6 kW/m². The heat transfer coefficient as well as Nusselt number for the different conditions under study were estimated using the temperature distribution obtained from a data acquisition device and appropriated post-processing. The use of fluid extraction through induced draft generated a significant increase in heat transfer in the area under the nozzle, obtaining values ranging from 290 up to 1500 W/m².°C.

RESUMEN: Una investigación experimental se ha llevado a cabo para evaluar la transferencia de calor en una configuración modificada de un chorro radial sumergido, por medio del cual se puede extraer el fluido directamente debajo de la boquilla, en busca de una mejora en la velocidad de transferencia de calor. Los experimentos se llevaron a cabo para las siguientes gamas de parámetros que rigen el fenómeno: boquilla de 16 mm de diámetro, distancia entre boquilla y placa entre 10 mm a 20 mm, número de Reynolds que oscila entre 10.000 y 20.000, y calor de 10,2 – 13,6 kW/m². La transferencia de calor se estima a través de la distribución de temperatura obtenida por medio de un dispositivo de adquisición de datos y un apropiado post-procesamiento, lo que hace posible determinar el coeficiente de transferencia de calor y el número de Nusselt para las diferentes condiciones en estudio. El uso de la extracción de fluido a través de tiro inducido genera un aumento significativo en la transferencia de calor en el área debajo de la boquilla, obteniendo valores desde 290 hasta 1500 W/m².°C.

1. Introduction

Radial jets have a great importance in industrial applications like heating, drying of paper, metals cooling, and recently cooling of micro-component. However, electronic manufacturers are always in search of creating more powerful and smaller devices. As a result, the heat generated during the operation of these components is higher every day, and cooling technologies are pressed to ensure a suitable heat removal for future generations of these devices.

Previous research has been conducted on the issue of radial jet, the efforts in past years were directed to the study of the influence of factor in heat transfer capability of normal configuration of jets; this research proposes a new configuration of radial jet aiming to improve the stability of fluid structure and heat transfer.

The study of impinging jets as a cooling medium holds a great significance due to increasing heat flux in electronic circuits. The jet bending degree in its path to the surface has been studied [1]; this analysis evaluates the dependence of flow parameter at different nozzle conditions such as exit angle, radius, and distance from nozzle exit to surface. Other researchers [2-7] conducted heat transfer analysis in order to describe and improve jet performance. Researchers indicated that heat transfer rate considerably improved when using radial nozzles, and in general, radial

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jet reattachment produces higher heat transfer coefficients than axial jets. Subsequently, [8-12] conducted studies which compared the effects of free and submerged jets in the heat transfer coefficient. Their analysis indicated that if the jet is submerged, the heat transfer coefficient can be increased up to 25%, and this ratio can vary dramatically with nozzle to surface distance.

In an attempt to increase the heat transfer from the cooling process [13], boiling heat transfer was studied as a cooling mechanism for electronic devices. Results showed that jet velocity and diameter have great influence on the heat transfer coefficient. Higher speeds lead to greater heat transfer for single-phase fluid regime while its effect on the boiling regime is not as significant for certain levels of speed. The hydrodynamic and thermal characteristics of a free jet have been researched [14] by studying the influence of the temperature and the flow velocity on jet structure. It was found that the influence of the nozzle-surface distance on Nusselt was mild, but the average Nusselt number increased with the nozzle diameter for the same Reynolds number. Three zones were identified: impingement of the jet, parallel flow and hydraulic jump area, for each one of them, the heat transfer coefficient depends on the flow rate.

In recent years [15], studies correlated and compared the rate of transfer for different radial positions and some surface nozzle distances in a submerged circular jet. Results showed that far from the stagnation point, the exponent that characterizes the flow pattern of the working fluid increases. Correlations for submerged jet as cooling systems under steady state and transient conditions were developed [16]. The study showed that the transient state is affected by the temperature rise and the flow velocity, with temperatures and high velocities easily reaching faster stability.

In addition [17], research was carried out to understand the heat transfer process in which the jet was induced by pulse. For nozzles angles ranging from 0 to 20 degrees and Reynolds from 1,683 to 2,366, air is forced to pass through a pulse supplying system, increasing heat transfer when the pulse number of the cycle is increased. For submerged jets [18], with Reynolds ranging from 10,000 to 30,000, and dimensionless distance-jet outlet surface of 0.5 to 8, it was found that for small distances between nozzle and surface (<2 diameters), peaks appear in the radial distribution of heat transfer due to abrupt increase in surface turbulence.

The structure of vortexes in radial jets when placed in front of a flat plate has also been studied [19]. Results show the influence of factors such as surface-nozzle distance and the Reynolds number in the level of vorticity in the jets. Research to observe the behavior of a modified in-line jet using a coaxial system was performed [20], the analysis reports the pressure distribution as well as the heat transfer coefficient for the jet area of influence. Experimental work [21] has analyzed the influence of jet geometry in the heat transfer characteristics. It is concluded that some geometries promote heat transfer.

All these studies show the importance of developing research in this area due to the existence of many opportunities for improvement in these systems.

2. Experimental setup

2.1. Testing system

The structure consists of an acrylic tank, 600 x 600 x 400 mm height. It has three connections, two for water recirculation in order to maintain flow conditions, and the third to deliver fluid to the nozzle, generating the radial jet. It also allows fluid extraction from the low pressure region directly below the nozzle.

A complete scheme of the testing systems is shown in Figure 1. The radial nozzle configuration is shown in Figure 2.

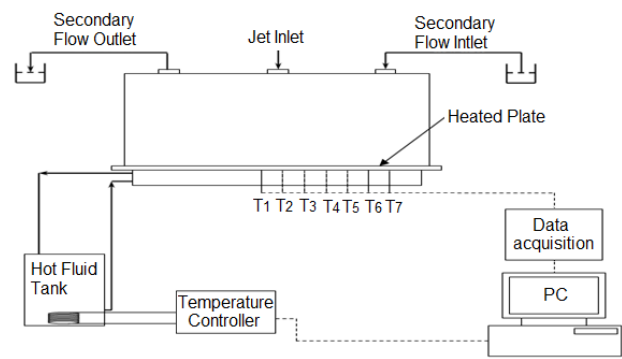


Figure 1 General configuration

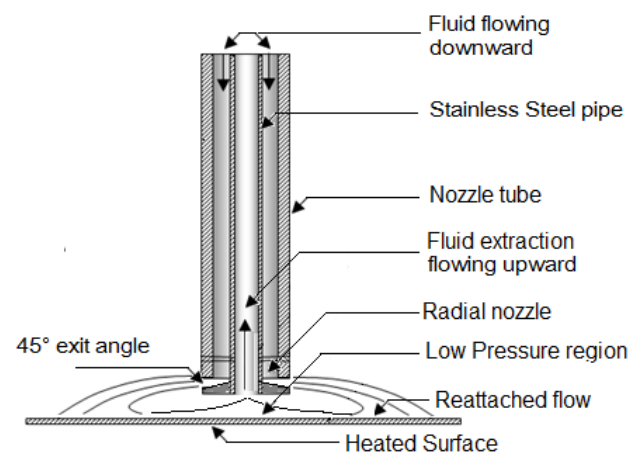


Figure 2 Radial Jet Nozzle with fluid extraction

To generate the radial jet, an acrylic tube, with inner diameter of 19 mm is attached to the tank cover. A 304L stainless steel nozzle, 450 mm long, 12.6 mm outer diameter, and 8 mm inner diameter is located in the center of the acrylic tube, creating an annular flow between the acrylic tube and

the stainless steel pipe. This pipe is used to extract the fluid from the area located under the radial nozzle. At one end, the tube has a 18mm diameter disc with an exit angle of 45° relative to the tube. For the impact surface, a 304L stainless steel plate, 2 mm thick is located under the nozzle. Below this plate, a heating system is located along the control system. The power supply system is also located under the plate, and it is used to provide the required power to bring the surface to the desired temperature.

2.2. Heating system

The heating system consists of two tanks. The first one with 0.5 m high and 0.25 m inner diameter has underwater electrical resistance. This electrical heater is used as the final control element in a system designed to keep the temperature at a desired value. The interface was programmed in LabVIEW to acquire the signal from a temperature sensor type LM35 which is located at the tank outlet, this signal is processed by a virtual PID controller. A 0-4 VDC system is used to power the solid state relay which allows power to be supplied to the electrical resistance to maintain the temperature set point.

The second tank has a square cross section area, 0.5x0.5m by 0.1 m in height. This tank is connected to the radial nozzle using thermally insulated hoses. It provides the fluid to the required temperature, in order to calculate the heat power transferred in the process. LM-35 temperature sensors are located at the inlet and outlet of this tank and its signal is acquired and processed through Labview.

2.3. Data Acquisition

To measure the temperature of the plate and fluid during testing, sensors type LM35 are used. These sensors essentially provide a voltage depending on the temperature of the contact surface, and this voltage is proportional to temperature (10mV equal to 1 ° C). To collect the information, a data acquisition card NI 6025E and a Labview programmed interface are used, through which the temperatures are recorded.

2.4. Experimental study methodology

For the submerged radial jet problem, the factors as well as the levels' range are established. Also, the response variable is chosen, temperature. The experimental design is selected, and the tests are conducted (runs) to finally proceed analyzing the data and draw conclusions. The procedure used for the experiment has the following stages:

Stage 1. It is used to design the experiment to be carried out. The factors included are: surface to nozzle distance, plate temperature, and Reynolds number. In addition, there are constant factors, such as the fluid used, water; and non-controlled factors such as ambient temperature. Due to this, the entire experiment was carried out at

conditioned laboratory temperature. Prior experimentation showed that the process stabilizes around 200 second, and the data was captured up to 300 seconds. From previous experiments [16], the variables range were selected. Two heights were chosen for nozzle to surface distance: 10 and 20 mm. Reynolds numbers used in the experiment process guarantee the minimum and maximum values required to generate the reattachment on the plate, 10,000 and 20,000. The plate temperature chosen for the experiment was based on normal operating temperatures of electronic devices: 50 to 80 °C, which represents 10.2 and 13.6 kW/m². The response variable considered was temperature, which provides the required information about the process.

Stage 2. After defining the levels of the factors, the experimental design was chosen. The goal is to determine the significant factors. The experiment considered was a 2³ factorial design, corresponding to the number of variables under study. Design Expert® was used to randomize the experimental runs.

Stage 3. The runs are executed according the organization obtained from Design expert®.

Stage 4. After testing completion, data analysis is developed by identifying significant factors that allow description of radial jet behavior when induced draft is used for removing fluid from the area below the nozzle.

3. Experimental model

Temperature difference is related to the heat transfer coefficient as presented in Eq. (1):

$$h = \frac{q_{conv}}{A_p (T_p - T_j)} \quad (1)$$

Where h is heat transfer coefficient, q_{conv} is convective heat transfer, A_p is the heated plate area, T_p is the plate temperature, and T_j is the jet temperature. The convective heat flux is calculated according to Eq. (2):

$$q_{conv} = q_{gen} - q_{cond} - q_{rad} \quad (2)$$

Where q_{gen} , q_{cond} , and q_{rad} represent heat generated, conducted and radiated. The conduction and radiation losses are minimal. The first due to insulation employed in the system, and second because the temperatures considered in experiment are low and the temperature difference among the surfaces is quite small. Heat transfer is calculated using inlet and outlet temperatures in the heating tank. Eq. (3) to (5) present the energy balance, where h represents the fluid enthalpy:

$$\dot{q} - \dot{w} + \sum \dot{m} h_{in} - \sum \dot{m} h_{out} = \frac{de}{dt} \quad (3)$$

$$\dot{q} = \dot{m} (h_{in} - h_{out}) \quad (4)$$

$$\dot{q}_{gen} = \frac{\dot{m}(h_{in} - h_{out})}{A_p} \quad (5)$$

Nusselt number is calculated according to Eq. (6):

$$Nu = \frac{\bar{h}d}{k} \quad (6)$$

Where d is the characteristic length of the flow and corresponds to the internal diameter of the stainless steel pipe. The average heat transfer coefficient is obtained from Eq. (7):

$$\bar{h} = \frac{q_{conv}}{\Delta T} \quad (7)$$

Reynolds number is obtained from Eq. (8):

$$Re = \frac{ud}{\nu} \quad (8)$$

Where u is the jet velocity evaluated at the exit of the nozzle, and ν is the kinematic viscosity evaluated at the nozzle temperature. The heat transferred to the system is given by Eq. (9):

$$\dot{q} = \dot{m}C_p\Delta T \quad (9)$$

This set of equations are needed to perform the data reduction and determine the required parameters in the analysis.

4. Results and discussion

4.1. Factorial Design

To analyze the degree of significance for each factor in the phenomenon, a 2^3 factorial design is proposed and a random experiment is generated. Table 1 shows the factor's levels.

Table 1 Factor levels

Factor	Symbol	Units	Level	
			Low	High
A: Surface-nozzle distance	Xp	mm	10	20
B: Reynolds	Re	Non dimensional	10×10^3	20×10^3
C: Surface Temperature	Tp	°C	50	80

Table 2 Analysis of variance

Source	Sum of squares	Degrees of freedom	Mean square	f value	p value
A	365.5	1	365.5	8.15	0.04
AC	313.0	1	313.0	6.98	0.04
ABC	406.2	1	406.2	9.06	0.03
Residual	179.3	4	44.8		
Total	1264.1	7			

The ANOVA for Nusselt shows that in the range studied, the most important factor in the response is the nozzle surface distance and its interactions with the plate temperature and the flow rate. Table 2 shows the analysis of variance for the experiment. According to the results, there is no evidence showing violation of the normality criteria, independence and homoscedasticity. It is considered that the statistical analysis is valid for the data studied.

4.2. Heat transfer cooling system

The behavior of the heat transfer coefficient when using a radial jet is well-established and is known for its

advantages; however it is also known that in the area directly under the jet, heat transfer is affected by the unsteady situation created by the periodic removal of mass [1]. In this research, the fluid removal from the recirculation zone is studied in order to increase the heat transfer process while maintaining a steady condition. Figures 3 and 4 show the temperature distributions achieved when initial plate temperature is 80 °C and 50 °C respectively. It can be seen that the final temperature of the target area is lower than the rest of the plate, which constitutes an important step since it is possible to increase heat transfer in the objective area using induced draft which is the main purpose of this study.

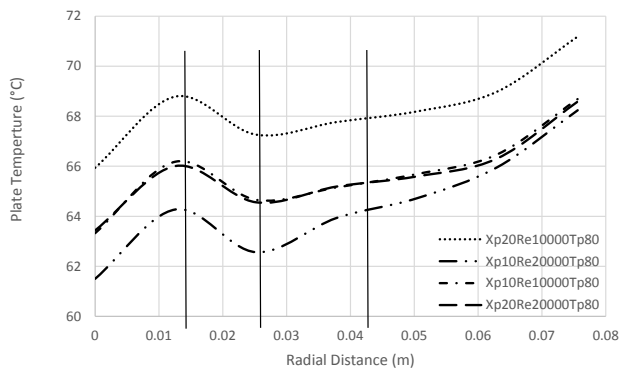


Figure 3 Plate final temperature distribution.
Plate initial temperature: 80 °C (13.6 kW/m²)

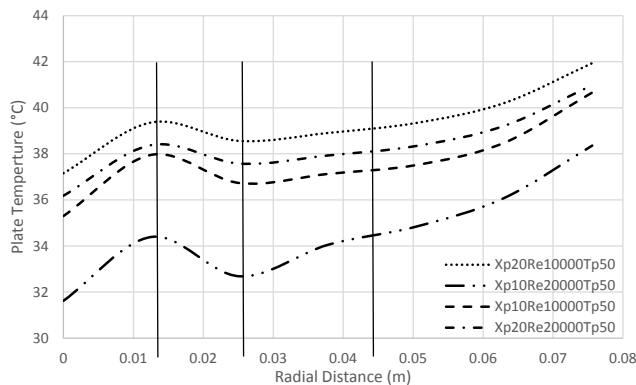


Figure 4 Plate final temperature distribution.
Plate initial temperature: 50 °C (10.2 kW/m²)

It is also noticed that there are two points with minimum temperatures. One located at the center of the plate ($r = 0$ m), and it is created by the fluid being removed from the bottom of the nozzle. At this condition, the fluid is able to remove a large amount of heat due to its low temperature. Furthermore, as the fluid moves from the point where it reattaches ($r = 0.025$ m) to the center, the area is being reduced creating an acceleration in the fluid being removed through the pipe connected to the bottom of the radial nozzle. These two situations, velocity increase and low temperature help to enhance the heat transfer coefficient in this area. The flow being removed, moves upward through the center of the pipe.

The second low temperature point ($r = 0.025$ m) is created by the radial jet reattaching over the flat plate. The reattachment of the fluid over the heated plate, creates two boundary layers, one growing toward the center of the heated plate, while the other grows from the reattachment zone to the external radius of the heated plate. The growth of a boundary layer is associated with a maximum heat transfer coefficient due to the minimum thickness of the boundary that represents a very small thermal resistance. Considering the fluid moving from the reattachment zone ($r = 0.025$ m) to the center of the heated plate ($r = 0$ m), it is noticed that the temperature increases up to a maximum

($r = 0.013$ m), and then it decreases. The first part, (0.013 m $< r < 0.025$ m) presents an increase in the temperature due to the growth of the boundary layer, that increases the thermal resistance and the ability of the fluid to remove the heat. In the second part (0 m $< r < 0.013$ m), the temperature decreases due to the acceleration of the fluid. The velocity increases with the negative square power of the radius (r^{-2}). The fluid is considered incompressible. It is noticed, that at the first part, the governing phenomenon is the growth of the boundary layer, while in the second part, the governing phenomenon is the velocity increase and regime change, from laminar to turbulent.

Downstream ($r = 0.044$ m), it is noticed that the temperature presents another inflexion point that could be associated with the boundary layer turning turbulent.

The heat transfer coefficient was calculated according to the methodology presented. The values attained are presented in Figures 5 and 6.

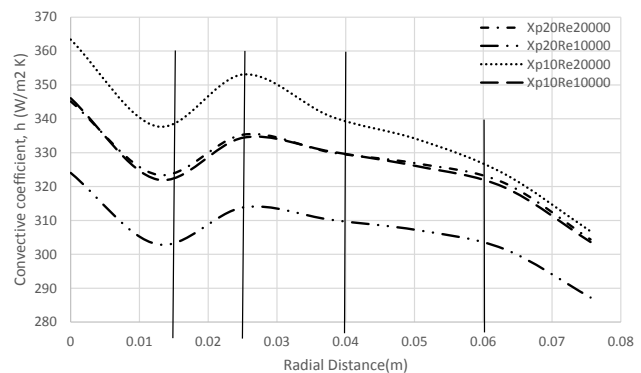


Figure 5 Heat transfer coefficient distribution.
Plate initial temperature: 80 °C (13.6 kW/m²)

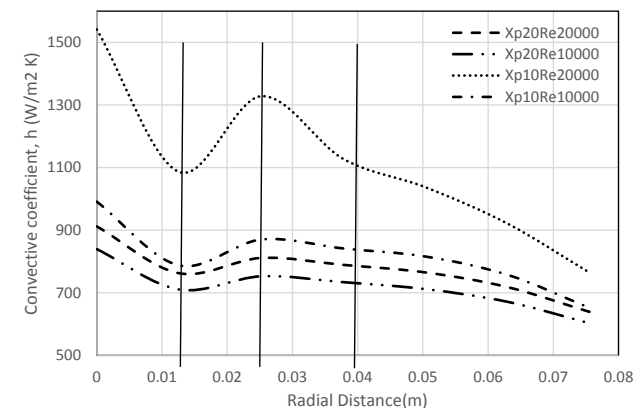


Figure 6 Heat transfer coefficient distribution.
Plate initial temperature: 50 °C (10.2 kW/m²)

At the center of the plate, there is a conjugation of situations: the fluid moving under the nozzle has the lowest temperature due to its quick removal from the tank and allows maximizing the heat transfer from the plate; the cylindrical conditions of the phenomena implies that

the minimum area is under the radial nozzle area. These two situations are combined to obtain the maximum heat transfer coefficient at the center of the nozzle. From the reattachment point ($0\text{ m} < r < 0.025\text{ m}$) to the center of the plate, the flow is coming radially toward the center due to the fluid removal at the central part of the nozzle. It is noticed that there is a peak ($r = 0.025\text{ m}$) where the radial jet impinges the plate, increasing the heat transfer due to boundary layer generation. The heat transfer coefficient slightly decreases due to boundary layer growth up to point ($r = 0.012\text{ m}$) where the acceleration of the fluid controls the heat transfer process, most likely turning the flow from laminar to turbulent, and at the center ($r = 0\text{ m}$) it reaches its maximum due to the minimum area at that point.

From the reattachment zone, increasing the radius ($0.025\text{ m} < r < 0.04\text{ m}$), the heat transfer coefficient decreases due to boundary layer growth. At ($r = 0.04\text{ m}$), it is noticed an inflexion and it could be credited to flow regimen change to totally turbulent. From that point to the end of the heated plate ($0.04 < r < 0.075\text{ m}$), the heat transfer coefficient decreases monotonically due to boundary layer growth, reaching its minimum value at the border of the plate due to temperature increment in the heat removing fluid and the layer growth due to radius increase.

It is very important to emphasize that there are then 2 zones with favorable characteristics for heat transfer in the proposed configuration. The first coincides with the previously known theory [1-4] ($0.012\text{ m} < r < 0.04\text{ m}$) that describes a ring of high-speed transfer between fluid jet impacting the heated plate and creating a reattachment zone, and the second that is the product of the proposed modification which allows greater control over the temperature of the area under the jet nozzle ($0\text{ m} < r < 0.012\text{ m}$).

4.3. Reynolds number

It is noticed from Figures 7 and 8 that the Nusselt number increases in all cases when the nozzle Reynolds number is increased. This was expected and has been reported by several researchers and it has been well described [3].

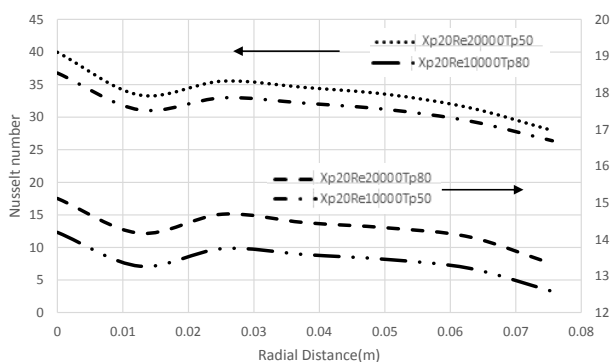


Figure 7 Nusselt number radial distribution for Xp20

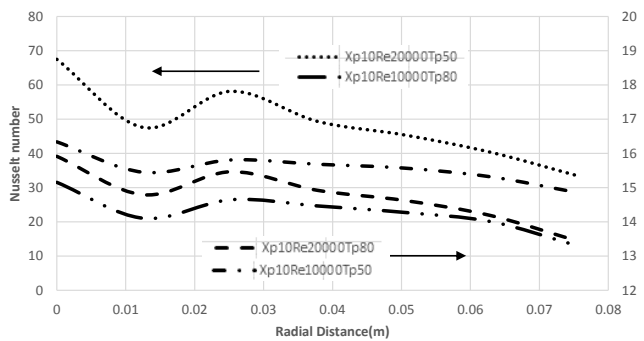


Figure 8 Nusselt number radial distribution for Xp10

It is important to notice from Figures 5 and 6, that the maximum heat transfer coefficient increases quite a lot, ranging from 320 up to 1500 W/m².°C at the center point.

4.4. Plate Initial Temperature and Power supply

For temperature, the range from 50°C to 80°C was studied. It is important to note that the initial temperature value of the plates is associated to a power supply of 10.2 and 13.6 kW/m² respectively. The heat transfer curves have a similar trend in all experiments performed. Figures 9 and 10 show the performance for the situations under study. Again, there is a curve with a maximum heat transfer at the point under the nozzle followed by a decrease and subsequent increase when approaching point of impact with the surface.

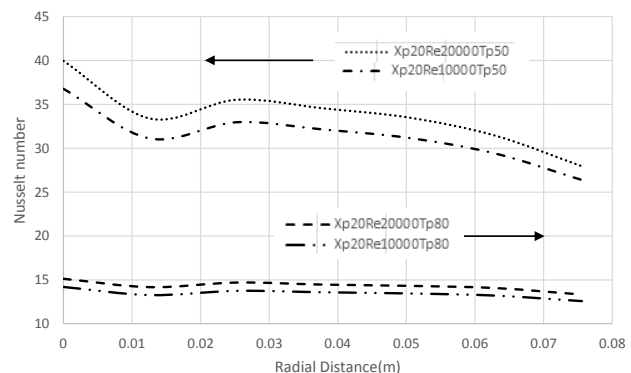


Figure 9 Variation with Temperature for Xp20

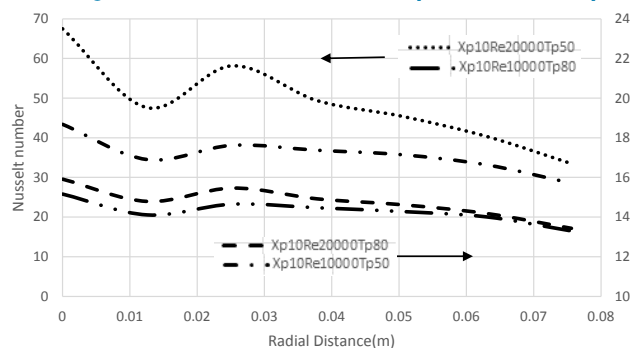


Figure 10 Variation with Temperature for Xp10

4.5. Surface-nozzle distance

Figures 11 and 12 show Nusselt number variation. For X_p , nozzle to impact surface distance, it is noticed that the heat transfer coefficient increases while decreasing X_p from 20 to 10 which are the ranges studied. The behavior of the Nusselt number is similar for surface-nozzle distance (X_p) obtaining higher values for $X_p = 10$ in all configurations analyzed which is in agreement with previous research [11-16] reporting this behavior in the phenomenon.

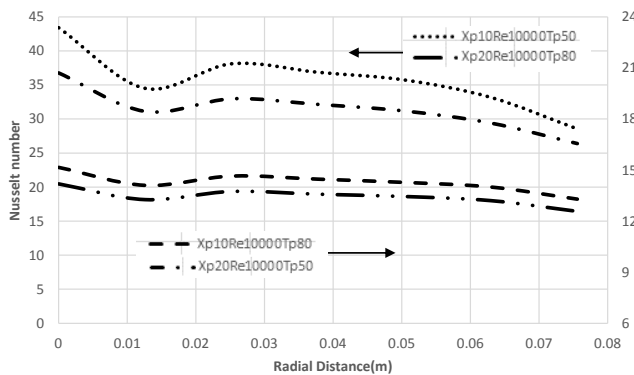


Figure 11 Variation with X_p for Re 10,000

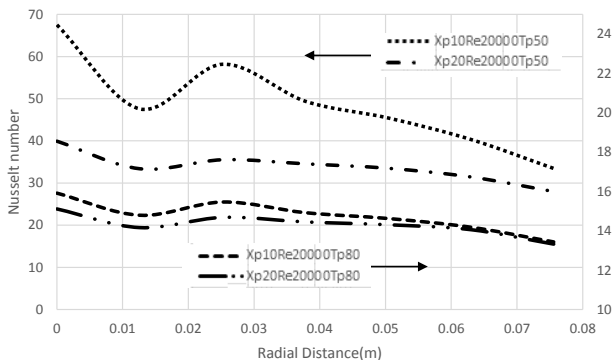


Figure 12 Variation with X_p for Re 20,000

5. Conclusions

The main parameters that determine heat transfer in a radial jet and its influence on the phenomenon have been established within statistically acceptable ranges, being surface-nozzle distance, and their interactions with the plate temperature and the flow rate, the most relevant variables that affect the performance of a radial jet with induced draft.

The use of fluid extraction through induced draft generated a significant increase in heat transfer in the area under the nozzle, because the extraction creates a regeneration zone that achieves heat transfer coefficients greater than those normally obtained in this type of device.

On the other hand, this study allowed finding that in general, the phenomenon behaves quite similar to a radial jet, and the induced draft only modifies the regeneration zone. This can be seen in Figure 7 to 12 which show that as we move away from the center line of the jet, heat transfer decreases, taking at least two peaks, one under the nozzle and the other at the impinging area, while in some other cases, depending on the Reynolds number, it can have an inflexion due to change in flow regime.

References

1. R. H. Page, L. Hadden, and C. Ostowari, "Theory for Radial Jet Reattachment Flow," *AIAA Journal*, vol. 27, no. 11, pp. 1500-1505, 1989.
2. S. Yao, Y. Guo, N. Jiang, and J. Liu, "An experimental study of a turbulent jet impinging on a flat surface," *International Journal of Heat and Mass Transfer*, vol. 83, pp. 820-832, 2015.
3. S. V. Alekseenko, A. V. Bilsky, V. M. Dulin, and D. M. Markovich, "Experimental study of an impinging jet with different swirl rates," *International Journal of Heat and Fluid Flow*, vol. 28, no. 6, pp. 1340-1359, 2007.
4. G. M. Carlomagno and A. Ianiro, "Thermo-fluid-dynamics of submerged jets impinging at short nozzle-to-plate distance: A review," *Experimental Thermal and Fluid Science*, vol. 58, pp. 15-35, 2014.
5. M. R. Pais, J. E. Leland, W. S. Chang, and L. C. Chow, "Single-Phase Heat Transfer Characteristics of Submerged Jet Impingement Cooling Using JP-5," in *4th Intersociety Conference on Thermal Phenomena in Electronic Systems (I-THERM)*, Washington, D. C., USA, 1994, pp. 178-183.
6. S. V. Garimella and B. Nienaydykh, "Nozzle-geometry effects in liquid Jet impingement heat transfer," *International Journal of Heat Mass Transfer*, vol. 39, no. 14, pp. 2915-2923, 1996.
7. J. Wu, J. Seyed, and R. H. Page, "Heat transfer and combustion characteristics of an array of radial jet reattachment flames," *Combustion and Flame*, vol. 125, no. 1-2, pp. 955-964, 2001.
8. H. G. Lee, H. S. Yoon, and M. Y. Ha, "A numerical investigation on the fluid flow and heat transfer in the confined impinging slot jet in the low Reynolds number region for different channel heights," *International Journal of Heat and Mass Transfer*, vol. 51, no. 15-16, pp. 4055-4068, 2008.
9. M. M. Rahman, A. J. Bula, and J. E. Leland, "Conjugate Heat Transfer During Free Jet Impingement of High Prandtl Number Fluid," *Numerical Heat Transfer, Part B: Fundamentals*, vol. 36, no. 2, pp. 139-162, 1999.
10. A. J. Bula, M. M. Rahman, and J. E. Leland, "Numerical Modeling of Conjugate Heat Transfer during Impingement of Free Liquid Jet Issuing from a Slot Nozzle," *Numerical Heat transfer, Part A: Applications*, vol. 38, no. 1, pp. 45-66, 2000.
11. A. J. Bula, M. M. Rahman, and J. E. Leland, "Axial Steady Jet Impinging over a Flat Disk with Discrete Heat Sources," *International Journal of Heat and Fluid Flow*, vol. 21, no. 1, pp. 11-21, 2000.

12. M. M. Rahman, A. J. Bula, and J. E. Leland, "Analysis of Transient Conjugate Heat Transfer to a Free Impinging Jet," *Journal of Thermophysics and Heat Transfer*, vol. 14, no. 3, pp. 330-339, 2000.
13. A. Tay, X. Hong, and Y. Cheng, "Cooling of Electronic Components with Free Jet Impingement Boiling," in *8th Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITHERM)*, San Diego, USA, 2002, pp. 387-394.
14. J. B. Baonga, H. Louahlia, and M. Imbert, "Experimental study of the hydrodynamic and heat transfer of free liquid jet impinging a flat circular heated disk," *Applied Thermal Engineering*, vol. 26, no. 11-12, pp. 1125-1138, 2006.
15. D. W. Zhou and C. F. Ma, "Radial heat transfer behavior of impinging submerged circular jets," *International Journal of Heat and Mass Transfer*, vol. 49, no. 9-10, pp. 1719-1722, 2006.
16. M. Cely, A. Bula, and A. Ramos, "Experimental Study of Transient Heat Transfer Process in a Submerged Radial Jet," in *ASME International Mechanical Engineering Congress and Exposition*, Chicago, USA, 2006, pp. 563-568.
17. J. S. Furlow and D. L. James, "Convective heat transfer characteristics from combined mechanical and supply pulsed radial reattaching jets," *International Journal of Heat and Fluid Flow*, vol. 28, no. 1, pp. 178-190, 2007.
18. T. S. O'Donovan and D. B. Murray, "Jet impingement heat transfer – Part I: Mean and root-mean-square heat transfer and velocity distributions," *International Journal of Heat and Mass Transfer*, vol. 50, no. 17-18, pp. 3291-3301, 2007.
19. J. C. Duda, F. D. Lagor, and A. S. Fleischer, "A flow visualization study of the development of vortex structures in a round jet impinging on a flat plate and a cylindrical pedestal," *Experimental Thermal and Fluid Science*, vol. 32, no. 8, pp. 1754-1758, 2008.
20. N. Celik and H. Eren, "Heat transfer due to impinging co-axial jets and the jets' fluid flow characteristics," *Experimental Thermal and Fluid Science*, vol. 33, no. 4, pp. 715-727, 2009.
21. M. F. Koseoglu and S. Baskaya, "The role of jet inlet geometry in impinging jet heat transfer, modeling and experiments," *International Journal of Thermal Sciences*, vol. 49, no. 8, pp. 1417-1426, 2010.