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Cooling of the heated circular porous disc with a circular jet

Mert Gürtürk[1], Hakan F. Oztop[2]

Abstract

In this study, an experimental analysis has been performed on jet impingement onto close-cell porous material which is the shape of a circular porous disc which is aluminum foam. This porous material was located on the circular heater and temperature distribution, local and average Nusselt number were observed at the different situations. Experiments were carried out by considering different parameters which are Reynolds number (1048, 2620, 4192), the thickness of porous disc (6, 8, 10 mm) and heater power (3.6, 6.8, 10.5 W). The results show that the maximum average Nu number value is calculated as 464.06 at Re = 4192, P = 10.5 W. It is observed that for the lowest average Nu number value is obtained at P = 3.6 W and Re = 1048 for without porous material. The lowest average Nu number value is calculated as 94.201. It is found that the porous materials can be used to control heat transfer.

Keywords: Aluminum foam, jet impingement, heat transfer

1. INTRODUCTION

Porous materials are used for many applications in engineering. They have many advantages such as insulation, acoustic control, fire prevention and so on. They can be classified as open and close porous. Porous materials are used for enhancing heat transfer in cooling applications because they have more surface area than a flat surface. Heat transfer fluid can pass from inside open porous materials but cannot pass from inside close porous materials. In the literature, many studies can be found. Some of them are a discussion in this part of the study. Electronic devices and some parts of machines need to be cooled. In this perspective, researchers have studied cooling of the heated circular disc from a different angle. The close porous sheet which is aluminum was wrapped on a heater. Experimentally, occurring heat transfer was investigated as with and without porous layer. They found that the Average Nusselt number with porous layer sample vary between 90 and 130 [1]. In the same perspective, interactions of turbulent flow and porous media were carried out both experimental and numerical [2]. In the studies using impinging jets, cooling of samples which produce a significant amount of heat was carried out. The authors show that the Average Nusselt number for different nozzles distances change between 35 and 115 [3]. In the research manuscripts which have been studied on the impinging jet, many different parameters are considered. Some of them are different velocity, power, Ra-Gr-Richardson number and circumferential angles. Maximum local Nusselt number was calculated as 33 for Re number 1900

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[4]. In the last studies, using thermal camera has raised. For example, a thermal camera was used for investigating the effect of nozzle geometry on heat transfer characteristics. Average Nusselt numbers were calculated between 5 and 95 for different Reynold numbers [5]. Some authors chose Marc-Zehnder interferometer in their studies [4]. Impinging jet applications are encountered in many different industries. In the literature, numerical studies about jet impinging can be found [6]. Also, nanofluid was used in impinging jet studies [7]. Impinging cooling of open aluminum foam material was studied in different parameters which are Reynold number, the rate of the height of the heat sink and width of the slot jet nozzle, rate of length of the heat sink and width of the slot jet nozzle and porosity. The authors found that porous aluminum foam heat sink can enhance the heat transfer performance [8]. Not only impinging jet and porous material are used for heat transfer application, but also they are chosen for obtaining better flow distributions in many engineering applications. In this perspective, studies obtained better flow distributions can be found in the literature [9]. In terms of flow characteristics, jet impingement and channel flow conditions were studied for determining heat transfer and pressure loss and using porous foam increase heat transfer coefficient in both conditions [10]. Some numerical studies focus on the confined impinging jet on a flat plate and on a plate covered with a porous layer. Changing in different parameters which are permeability, channel blockage ratio, a variation of porosity and solid to fluid thermal conductivity ratio was observed in that study [11]. The shape factor of the porous material is one of the important parameters. Researchers studied for determining heat transfer characteristics of different shape porous blocks and they used an impinging jet for that study [12]. Studies using porous and impinging jet showed that the heat transfer rate increase between 50% and 90%. In this study, close porous material which is the shape of a circular porous disc and made from aluminum is used. This porous material was located on a circular heater and temperature distribution, local and average Nusselt numbers were observed in different situations. Obtained results are illustrated in result and discussion, but first, experimental methodology and theory are presented.

2. MATERIAL AND METHOD

Cooling effects of the aluminum porous disc located on a circular heater are studied in this study and the purpose of the study is to search for the answer of the question whether the aluminum porous disc can be used in an application which impinging jet is used. To do this, an experimental setup was constructed as in Fig. 1.

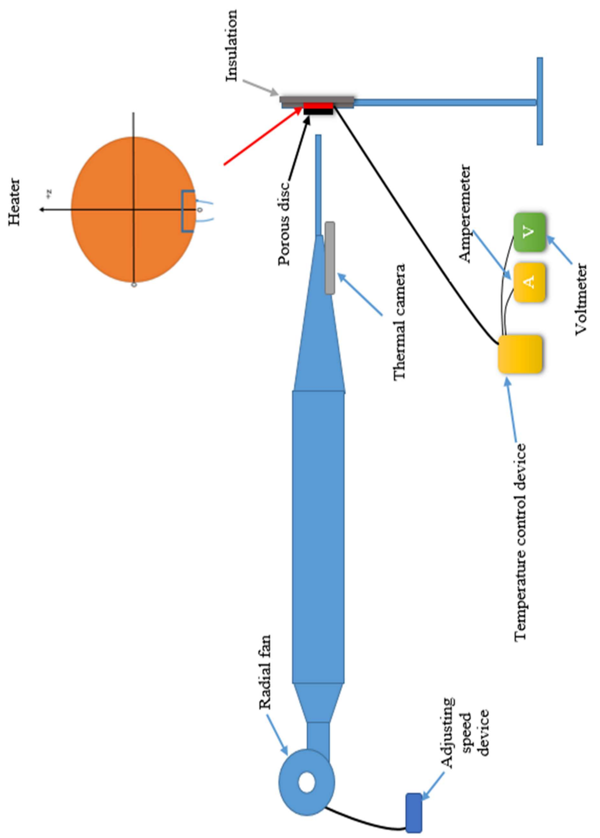


Figure 1. Experimental setup

Aluminum foam is used in many applications. For example, it used for flame insulation and acoustic control. Also, it is chosen to improve heat transfer performance by researchers and engineers, so the aluminum foam is used in this study. Experiments were carried out by considering different parameters which are Reynolds number (1048 – 2620 – 4192), the thickness of porous disc (6 – 8 – 10 mm) and heater power (3.6 – 6.8 – 10.5 W). The air which is heat transfer fluid is supplied by using a radial fan. Heater diameter is 10 cm and the length of the pipe is considered according to allow the fully developed flow. The circular heater is controlled by using the voltage transformer and constant heat flux is obtained from it by using a variac. Insulation application is applied edge and back of the circular heater. First, the circular heater was covered with thin aluminum sheet whose thickness is neglected and then the experimental study was carried out for considered parameters. Aluminum close porous material which has the same diameter with circular heater is placed on a circular heater and the same experiments are carried out with aluminum close porous materials. The heater power is determined by using Eq. (1).

$$\dot{E} = VI \tag{1}$$

where V and I symbolize the voltage and current, respectively.

$$\frac{\dot{E}}{A} = \frac{4\dot{E}}{\pi D^2} \tag{2}$$

In the Eq. (2), A is area and D is heater diameter. Eq. (3) is used for determined local convection heat transfer coefficient as follow:

$$h_i = \frac{\dot{E}}{\left[A\left(T_i - T_\infty\right)\right]} = \frac{\dot{E}}{\left[\frac{\pi D^2}{4}\left(T_i - T_\infty\right)\right]} \tag{3}$$

where T indicates both temperatures at i point for heater and jet. Re number is calculated by using Eq. (4).

$$\mathrm{Re} = \frac{uD_h}{\nu} \tag{4}$$

Reynold number indicates that fluid flow is turbulent or laminar. The hydraulic diameter is calculated as follow:

$$D_h = \frac{4A}{P} \tag{5}$$

P is jet cross-section circumference. Local Nusselt number is determined by using Eq. (6).

$$Nu_i = \frac{h_i D_h}{k} = \frac{4P}{\pi k D\left(T_i - T_\infty\right)} \tag{6}$$

where k is thermal heat conductivity. For calculating average Nusselt number, Eq. (7) is considered in the analysis.

$$Nu_{ave} = \frac{h_{ave} D_h}{k} \tag{7}$$

h_{ave} is average convection heat transfer coefficient.

$$\dot{E} = h_{ave} A\left(T_{ave} - T_\infty\right) \tag{8}$$

T_{ave} indicates the average temperature of the heater and it is calculated by using Eq. (9).

$$T_{ave} = \sum_i \frac{T_i}{n} \tag{9}$$

Obtained results from the analysis are presented in the next section of this study. Heat transfer effects obtained using aluminum close porous material are determined.

3. RESULTS AND DISCUSSION

An experimental procedure was carried out to the analysis of heat transfer and temperature distribution on a heated porous disc. Firstly, an aluminum sheet which thickness of it can be neglected due to being very thin was placed on a circular heater. Then, aluminum foam with close porous material shaped as the disc was placed on the circular heater. Variable parameters in experiments are with and without porous material, different heater power, different thickness of the porous material and different Reynolds number. For all situations, temperature distribution, local and average Nusselt number were observed. Local Nu number, temperature distribution throughout r_o / D_h and thermal camera images for Re number 1048, 2620 and 4192 are shown without porous for P=3.6 W in Fig. 2.

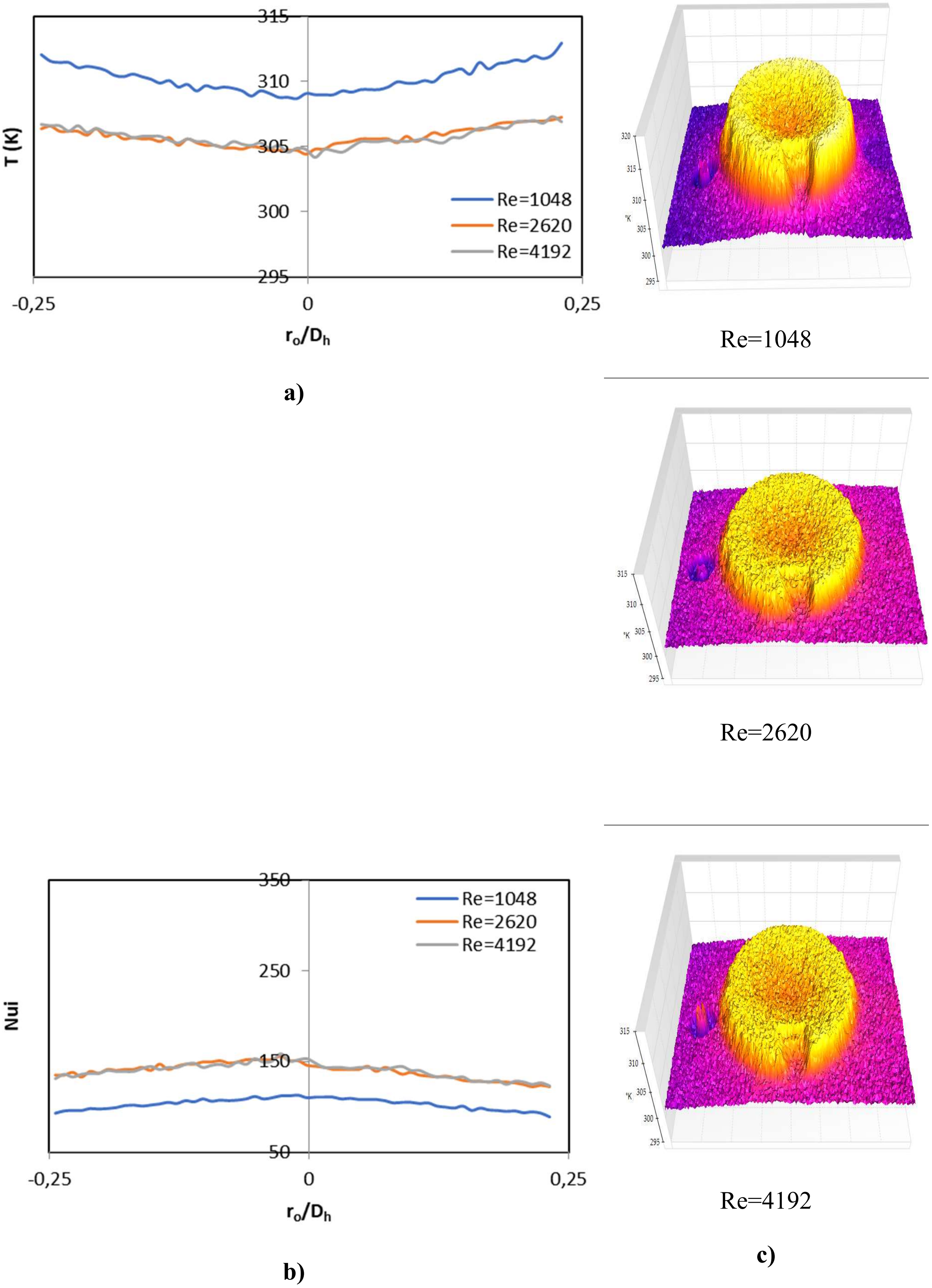


Figure 2. a) Temperature distribution b) Local Nusselt number, c) Thermal camera images for P=3.6 W without porous at different Reynold number

In Fig. 2, jet flow hits on the midpoint of the heater. The thermal camera images show the lowest temperature on the surface of the heater and the lowest temperature values are obtained from the midpoint of the heater. In parallel with this, local Nu number values raise in the midpoint of the heater. Measured results are illustrated in Fig. 3 for P = 6.8 W and without porous. In the Fig. 3, temperature distribution and local Nu number values obtained from this study raise due to increasing of the heater power which is P = 6.8 W for Re numbers at 2620 and 4192. Temperature distribution for Re = 1048 is higher than others due to impinging jet effects. Last results obtained for P = 10.5 W without porous are shown in Fig. 4. Local Nu number and temperature distribution values rise with the increase of the heater power. When results which are presented in the Figs. 2 – 4 are examined for Re=2620 and Re=4192, the jet has little effect on temperature distribution and local Nu number values. The impinging jet cooling effects are observed very clear from thermal camera images. A pit occurs in temperature distributions at these images because the impinging jet hits this point which is the midpoint of the heater. The same experimental procedure was applied for aluminum circular porous material at different thickness and heater power. Porous materials at different thickness are placed on the circular heater and temperature distribution, local Nu number and thermal camera images were obtained. Fig. 5 presents results obtained for P = 3.6 W and aluminum close porous material. The thickness of the porous disc is 6 mm. When results in Fig. 5 are compared with results obtained from for P = 3.6 W and without porous, it can be seen that porous material provides good cooling effects. In the experiments, perfect insulation is not provided as seen in thermal camera images. Around of the porous material is porous too, so this irregularity causes heat losses that can be neglected. The authors of this study neglect these losses. Maximum local Nu number and temperature are obtained as 153 and 309.1 K for P = 3.6 W and without porous but 209 and 304 K for P=3.6 W with porous which thickness of it is 6 mm, respectively. However, it can be seen that irregular temperature distribution and local Nu number values are obtained for aluminum close porous material. In Fig. 2, while local Nu number value at the midpoint of the heater is determined as 110, the temperature at the midpoint is measured as 309 K for Re = 1048, P = 3.6 W without porous. Also, the difference between local Nu number and temperature at the midpoint are 110 and 309 K for Ra=1048 and approximately 153 and 304 K for Re=2620 and Re = 4192 in Fig. 2. In the same perspective, when values in Fig. 5 are examined, these values are very close due to homogeny heat distribution. When these two situations are evaluated, it can be said that the porous material supplies homogeneous heat distribution. The surface area of the porous material is higher than a flat aluminum sheet, so local Nu number values in Fig. 5 give good results than the values presented in Fig. 2. Fig. 6 shows local Nu number, temperature distribution and thermal camera images for P=3.6 with porous which thickness of it is 8 mm. The whole experimental procedure is also valid for Fig. 6, but the only thickness of the porous material is changed for determining the effect of the thickness. Thickness parameter of the porous material can be important in the heat transfer process. When the thickness of the porous material increases, the depth of the pores of the material will also increase. In this situation, how heat transfer phenomena affect according to other situations are examined in this study. Almost, no significant difference is observed local Nu number and temperature distribution on the surface of the porous material in Fig. 5 and 6. However, the average Nusselt number can be said that which variations give good results for cooling. Fig. 7 presents local Nu number, temperature distribution and thermal camera images for P=3.6 W with porous (thickness = 10 mm). In the Fig. 7, when values which are local Nu number and temperature distribution are compared with the values in Fig. 5 and 6, it can be seen that Re number in Fig. 7 is more effective than others. For example, the values in Fig. 5 and 6 for Re=1048, 2620 and 4192 are very close, but local Nu number and temperature distribution at Re=1048 are separated from other values at Re=2620 and 4192 in Fig. 7. The effect of the use of porous material at P=3.6 W is clearly visible when examined in Figures 2, 5 - 7. It is understood that when the porous material is not used, the local Nusselt number value is around 150, while the porous material is used, the local Nusselt number value varies between 150 and 250. When the thickness value of the porous material with P = 3.6 W is changed, it can be seen that there is no significant difference between the results obtained for the 6 mm and 8 mm values. However, it is understood that the results obtained for Re = 2620 and 4192 of thick porous material are better than other results at P = 3.6 W. In the experiments used in 10 mm material, Nu number value is slightly above 250 for P = 3.6 W. In experiments on 10 mm material, the results obtained for Re = 1048 were observed to be very close to the results obtained from experiments using thin and medium thickness materials. The parameter of the thickness is examined at different heater power values. In the Fig. 7, when values which are local Nu number and temperature distribution are compared with the values in Fig. 5 and 6, it can be seen that Re number in Fig. 7 is more effective than others. For example, the values in Fig. 5 and 6 for Re=1048, 2620 and 4192 are very close, but local Nu number and temperature distribution at Re=1048 are separated from other values at Re=2620 and 4192 in Fig. 7. The effect of the use of porous material at P=3.6 W is clearly visible when examined in Figures 2, 5 - 7. It is understood that when the porous material is not used, the local Nusselt number value is around 150, while the porous material is used, the local Nusselt number value varies between 150 and 250. When the thickness value of the porous material with P = 3.6 W is changed, it can be seen that there is no significant difference between the results obtained for the 6 mm and 8 mm values. However, it is understood that the results obtained for Re = 2620 and 4192 of thick porous material are better than other results at P = 3.6 W. In the experiments used in 10 mm material, Nu number value is slightly above 250 for P = 3.6 W. In experiments on 10 mm material, the results obtained for Re = 1048 were observed to be very close to the results obtained from experiments using thin and medium thickness materials. The parameter of the thickness is examined at different heater power values. Fig. 8 – 10 show obtained results for P=6.8 W and at the different thickness values of the porous material. When the experiments for P = 6.8 W are examined, Figs. 3, 8 - 10 are taken into consideration. In experiments where no porous material is used, the maximum local Nu number value is around 250. However, in the experiments where the porous material is used, it is seen that the local Nu number value is changed between 250 and 450. It has been observed that the porous material increases the cooling effect. It seems that these porous materials improve heat transfer. When the thickness parameters of the porous materials are considered, there is no significant difference between the local Nu number values at different Re values. Fig. 11 – 13 show obtained results for P=10.5 W.

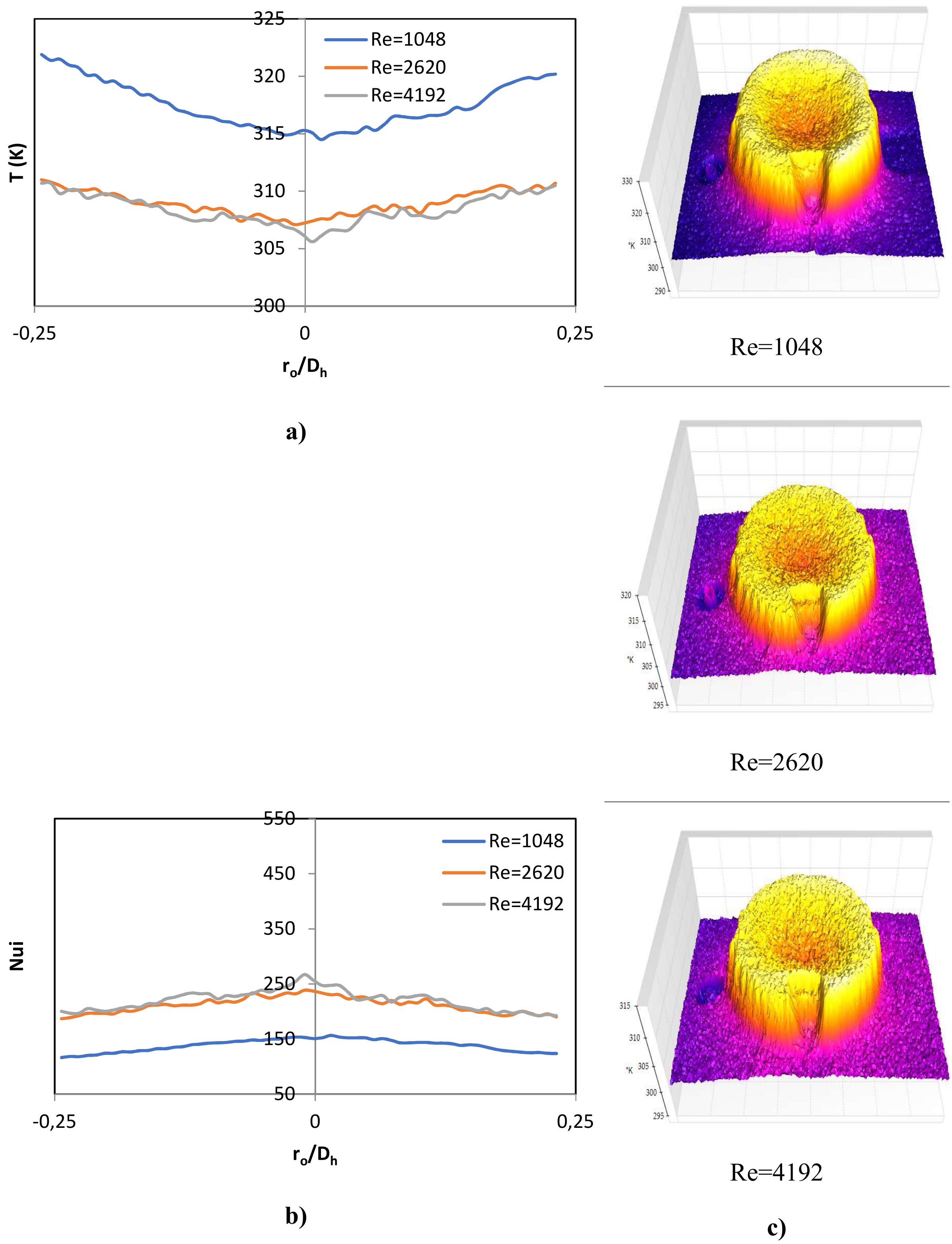
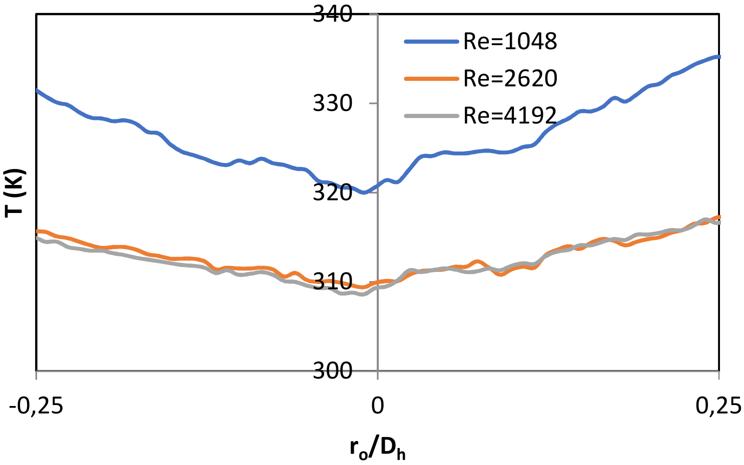


Figure 3. a) Temperature distribution b) Local Nusselt number, c) Thermal camera images for P=6.8 W without porous at different Reynold number



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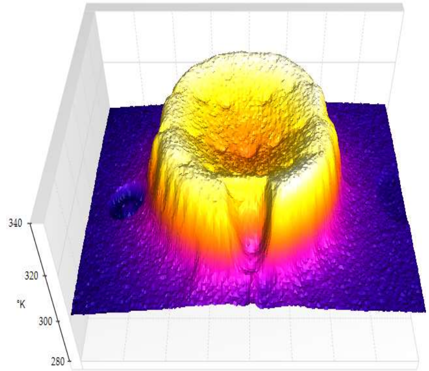
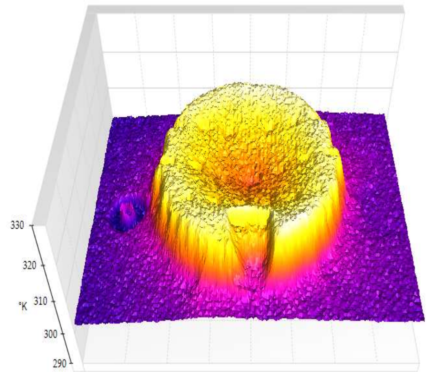
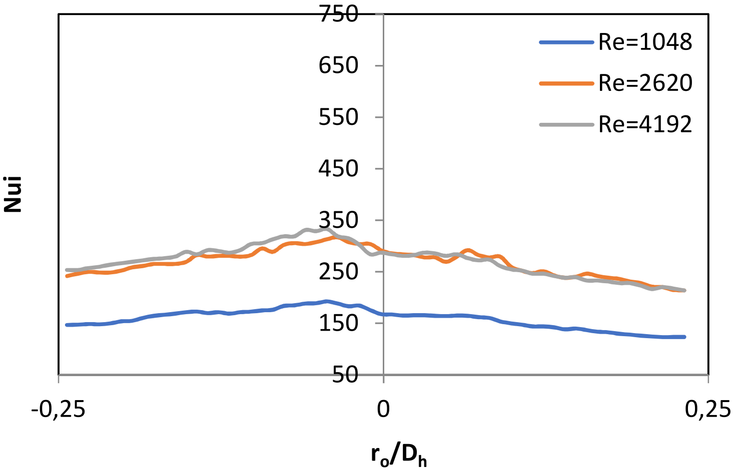


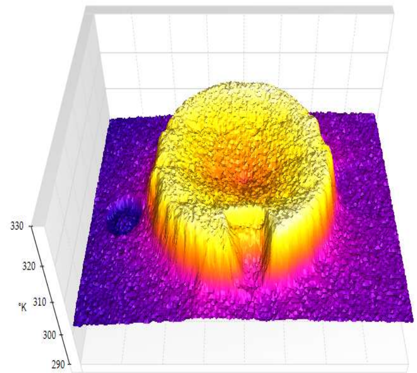
Re=1048



Re=2620



b)



Re=4192

c)

Figure 4. a) Temperature distribution b) Local Nusselt number, c) Thermal camera images for P=10.5 W without porous at different Reynold number

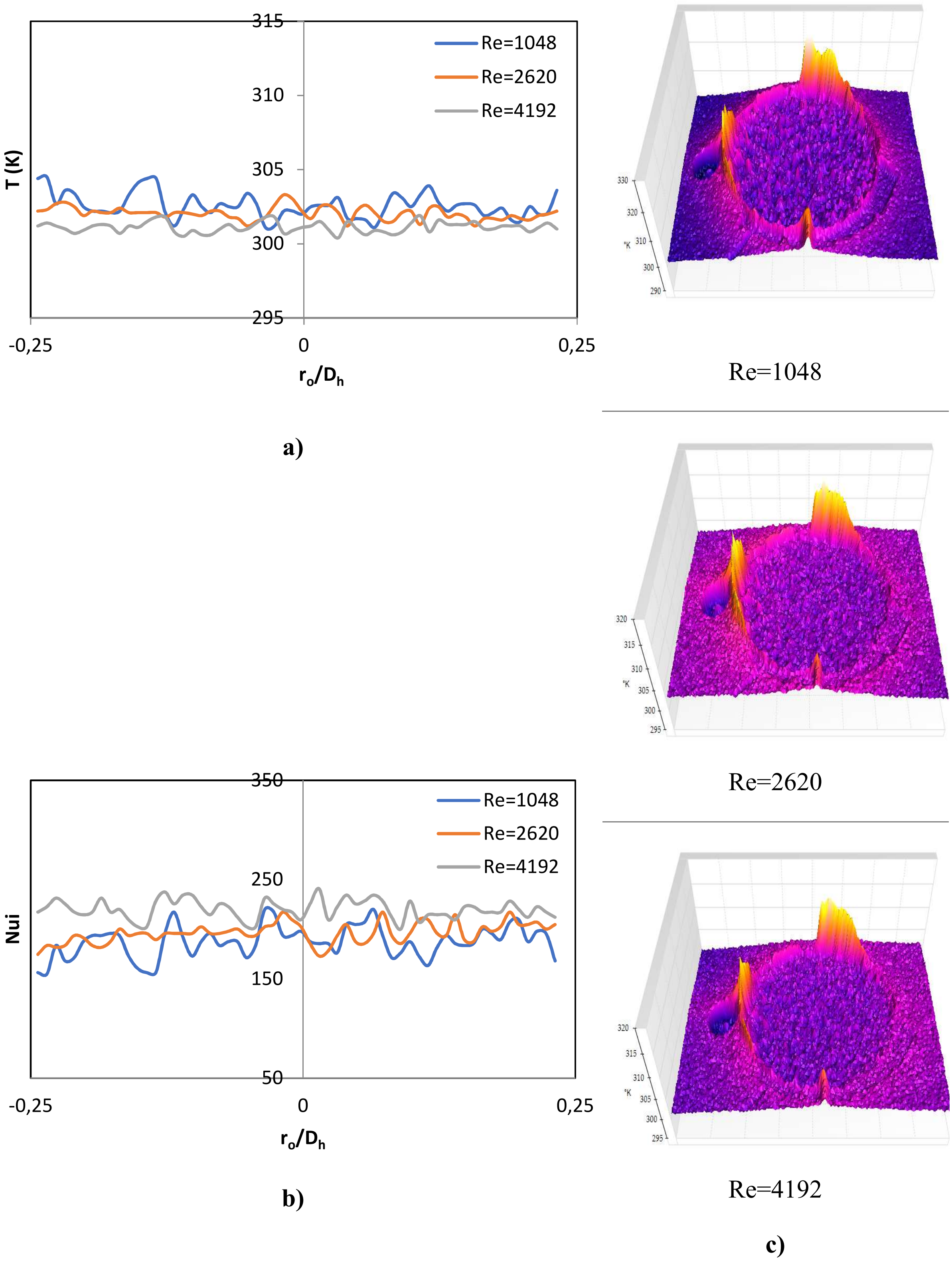
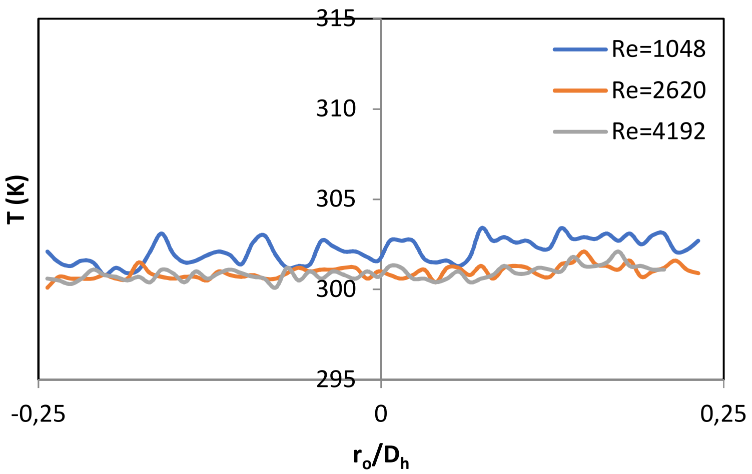


Figure 5. a) Temperature distribution b) Local Nusselt number, c) Thermal camera images for P=3.6 W with porous (thickness = 6 mm) at different Reynold number



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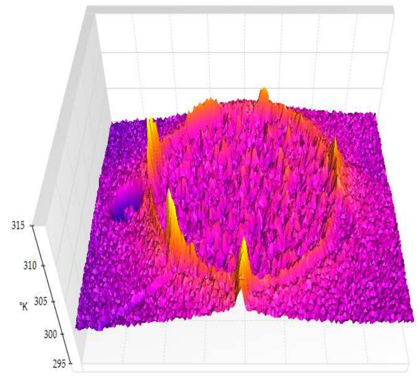
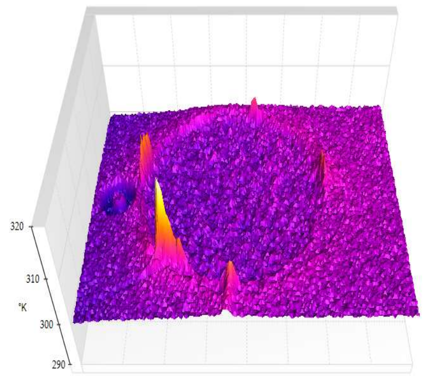
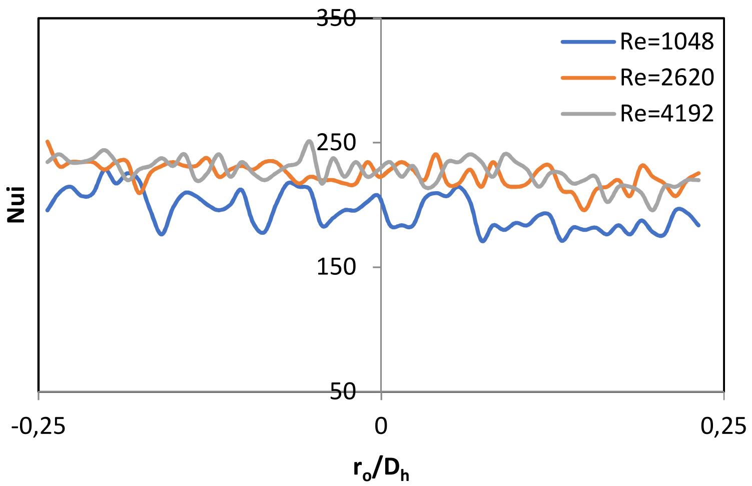


Re=1048



Re=2620



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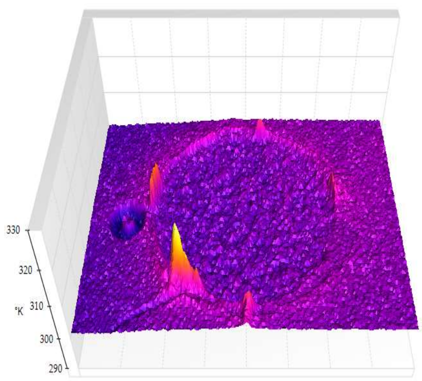


Re=4192

c)

Figure 6. a) Temperature distribution b) Local Nusselt number, c) Thermal camera images for P=3.6 W with porous (thickness = 8 mm) at different Reynold number

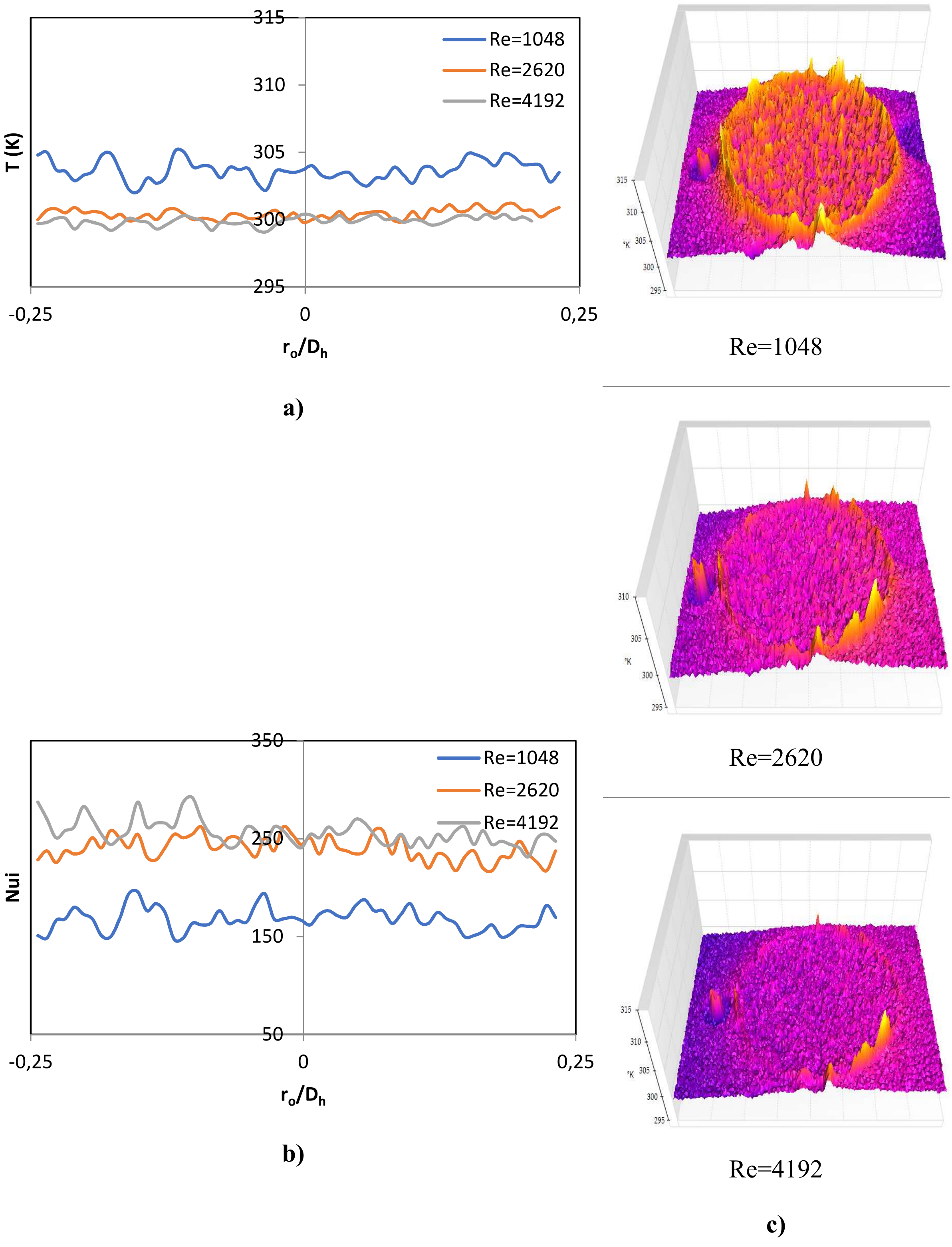


Figure 7. a) Temperature distribution b) Local Nusselt number, c) Thermal camera images for P=3.6 W with porous (thickness = 10 mm) at different Reynold number

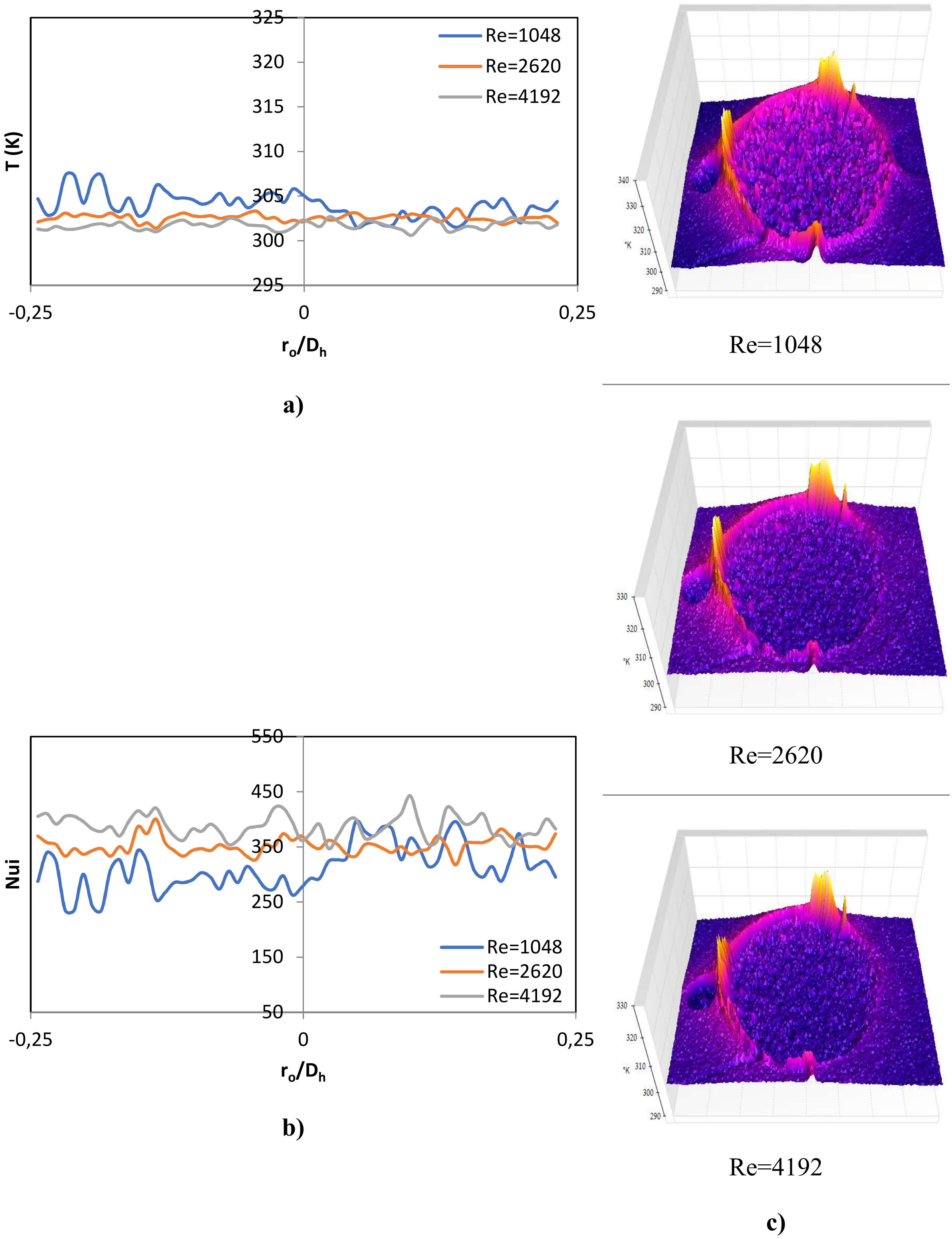


Figure 8. a) Temperature distribution b) Local Nusselt number, c) Thermal camera images for P=6.8 W with porous (thickness =6 mm) at different Reynold number

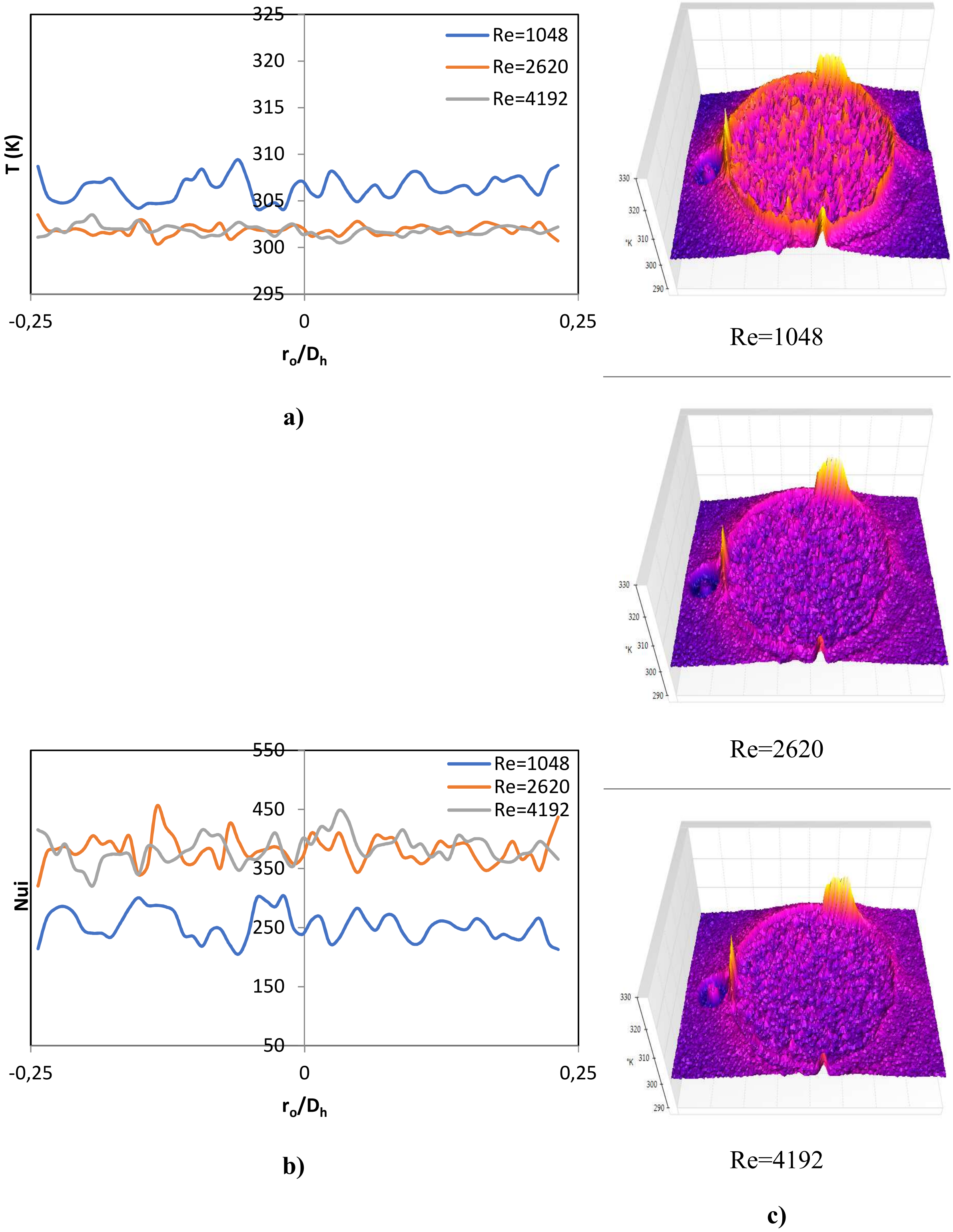
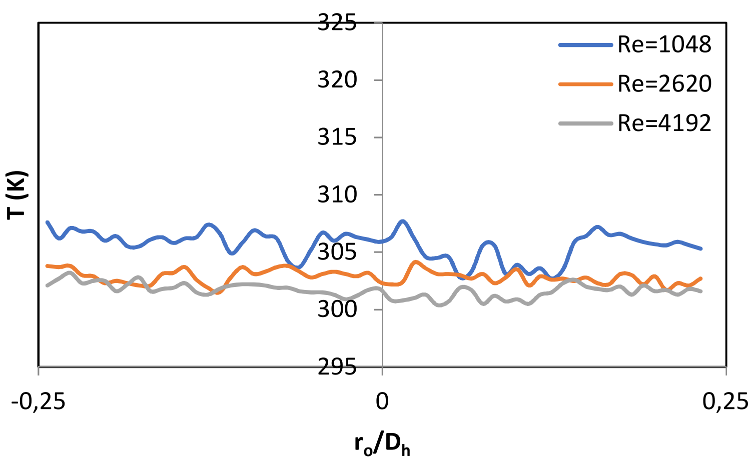


Figure 9. a) Temperature distribution b) Local Nusselt number, c) Thermal camera images for P=6.8 W with porous (thickness = 8 mm) at different Reynold number



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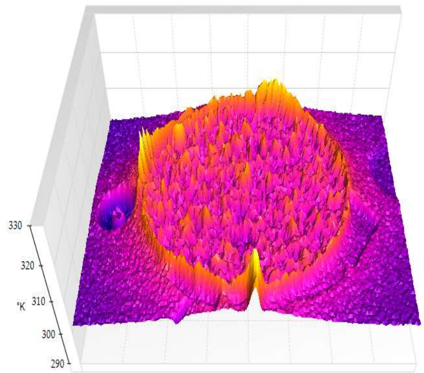
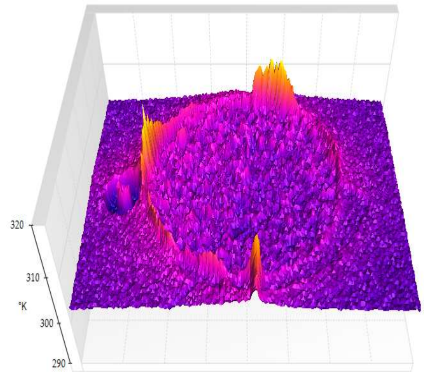
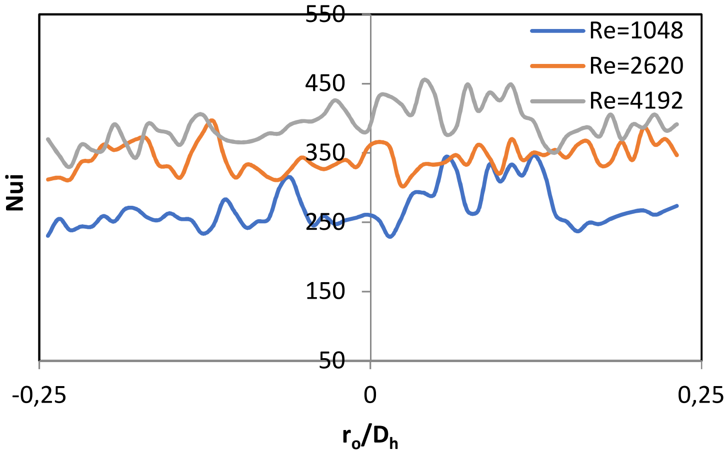


Re=1048



Re=2620



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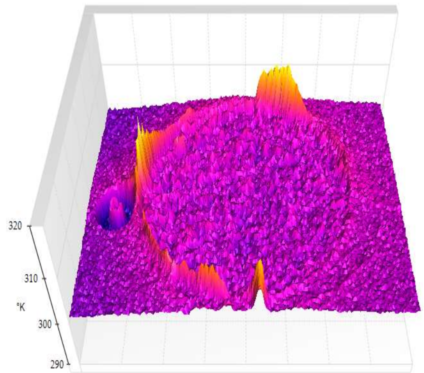
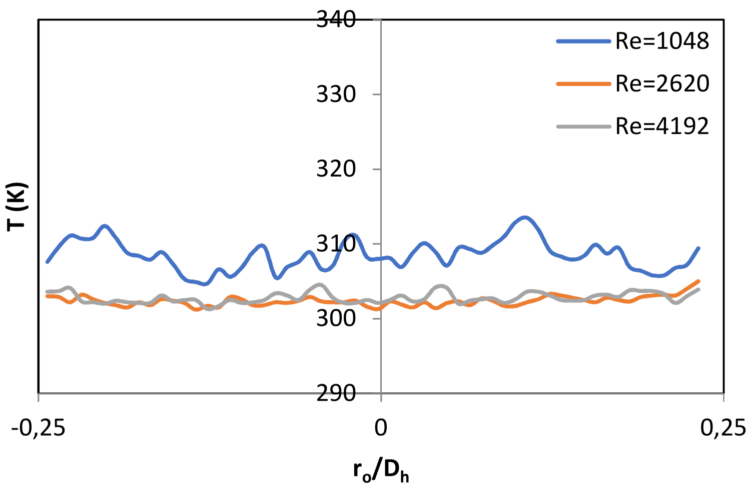


Re=4192

c)

Figure 10. a) Temperature distribution b) Local Nusselt number, c) Thermal camera images for P=6.8 W with porous (thickness = 10 mm) at different Reynold number



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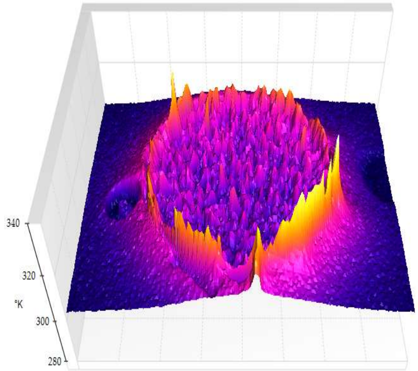

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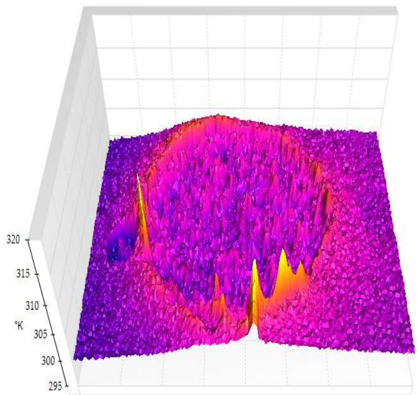
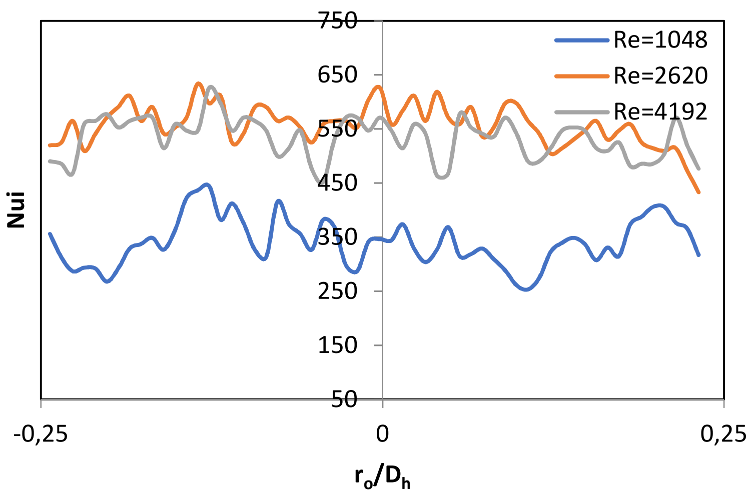


Re=2620



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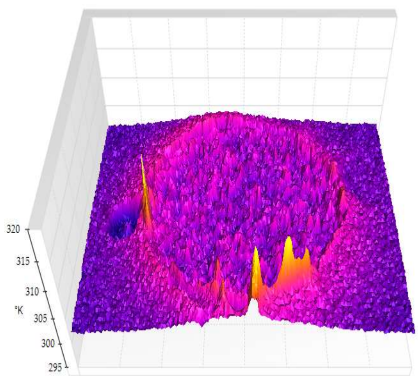
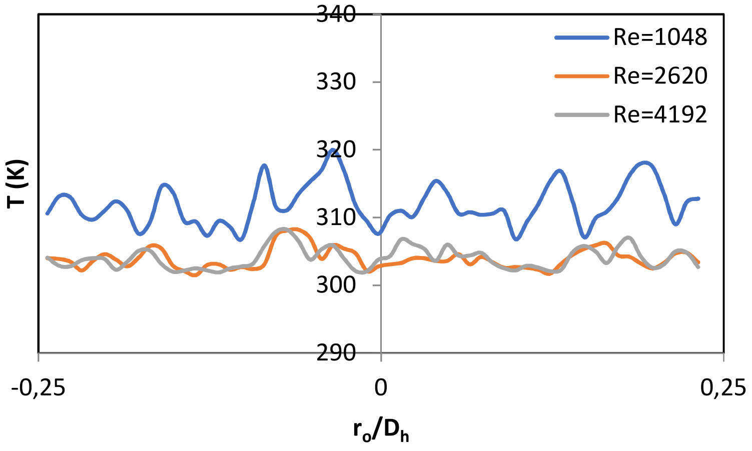


Re=4192

c)

Figure 11. a) Temperature distribution b) Local Nusselt number, c) Thermal camera images for P=10.5 W with porous (thickness = 6 mm) at different Reynold number



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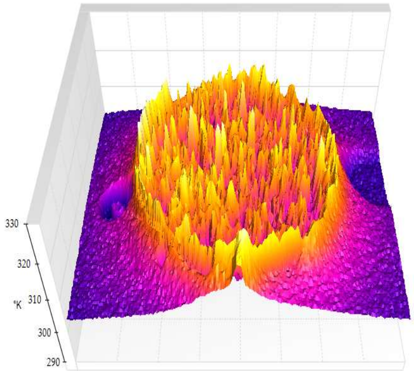

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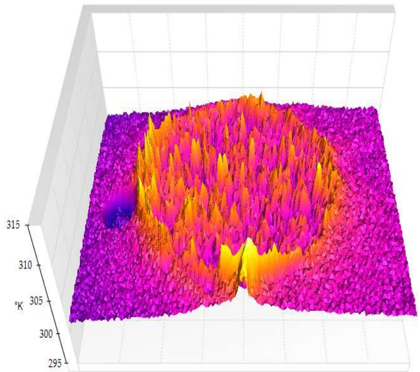

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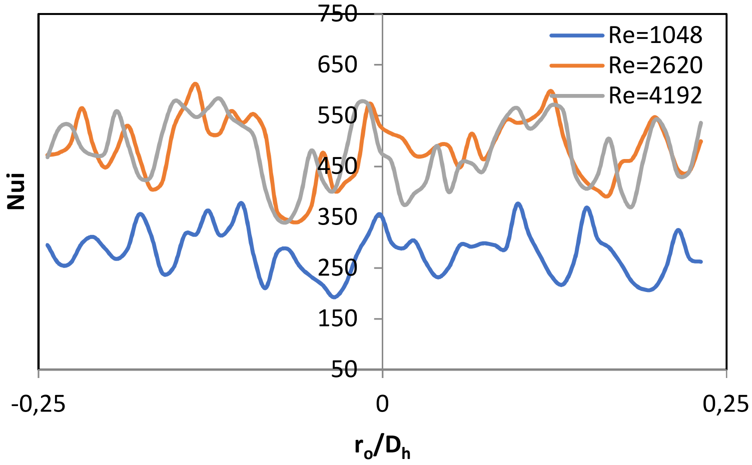

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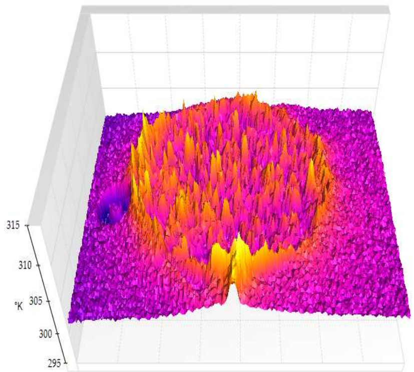

Re=4192

c)

Figure 12. a) Temperature distribution b) Local Nusselt number, c) Thermal camera images for P=10.5 W with porous (thickness = 8 mm) at different Reynold number

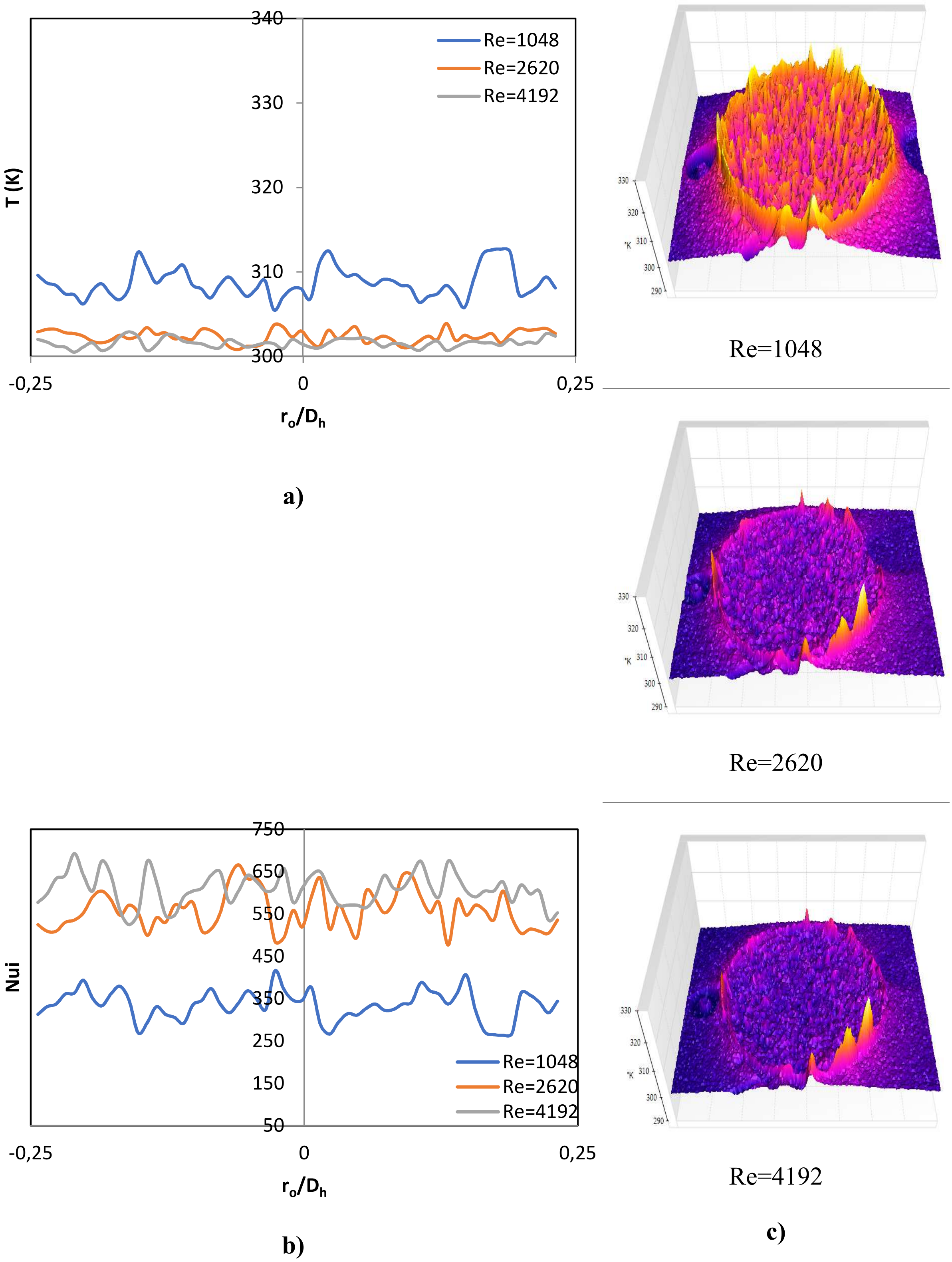

Figure 13. a) Temperature distribution b) Local Nusselt number, c) Thermal camera images for P=10.5 W with porous (thickness = 10 mm) at different Reynold number

When the experiments for P = 10.5 W are considered, results obtained in figures 4, 11 - 13 are considered. Experiments performed showed that the local Nu number values change from 150 to 350 in experiments for no porous material, while in the experiments where the porous material was used, the local Nu number values change from 250 to 650. It has been observed that the porous material improves heat transfer. However, considerable instability has been observed in the results obtained from experiments in which porosity materials are used for the irregularity of the porous material. It can be seen that in applications where instability is insignificant will not cause any problems. Another advantage of porous materials is light. The graphs of the average Nu number values obtained from experiments at the same heater power are shown in Figures 14-16.

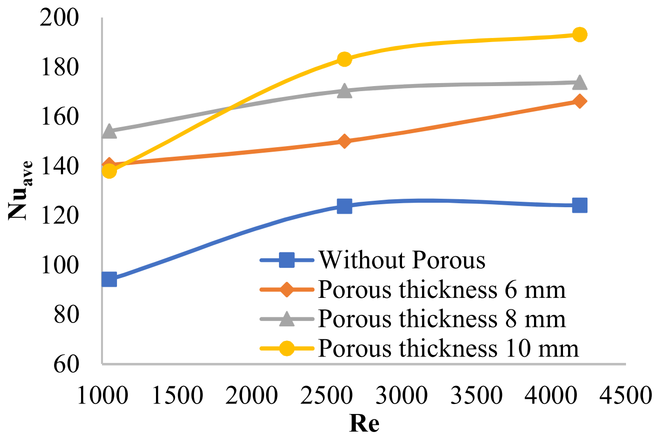

Figure 14. Average Nusselt number for P=3.6 W

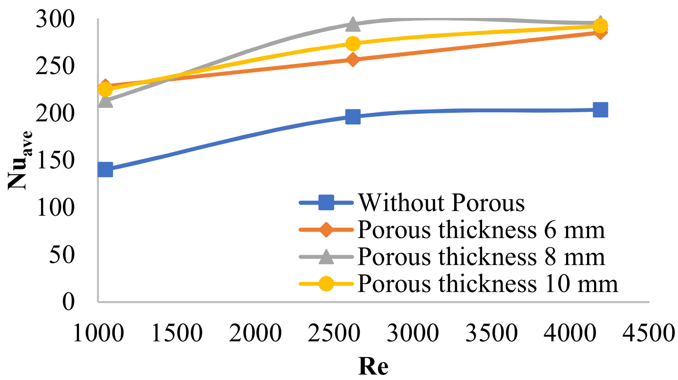

Figure 15. Average Nusselt number for P=6.8 W

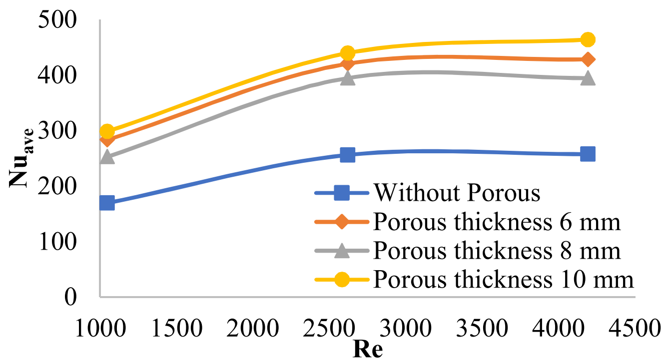

Figure 16. Average Nusselt number for P = 10.5 W

It can be seen that the porous materials provide high heat transfer in all cases. However, the irregularity at the average Nu number values can be seen. When the thickness parameter of porous materials is evaluated, it can be said that the thick porous material has better results than the others. The average Nusselt number values obtained at P = 3.6 W indicate that results obtained from the thick porous material for Re = 2620 and 4192 are better than the others. Considering the values in Figure 15, it is understood that thick porous material does not give very good results. Fig. 15 shows that heat transfer occurring thickness (8 mm) of the porous material at Re = 2620 is better than the others. Figure 16 shows that thick porous material has the best values at all Re numbers. The results obtained in a general framework can be evaluated. The average Nu number value can be considered in this perspective. When the average Nu number values are taken into account, it is seen that the best average Nu number value is obtained in the experiment which was carried out for Re = 4192, P = 10.5 W and thickness 10 mm. In the measurements and calculations made in this experiment, the maximum average Nu number value is calculated as 464.06. It is observed that for the lowest average Nu number value is obtained at P = 3.6 W and Re = 1048 for without porous material. The lowest average Nu value is calculated as 94.201. As the thickness of the porous material increases, the heat transfer area will increase. However, the air gap in the section between the porous material and the heater will increase and resistance to this gap is increased due to the low thermal conductivity of the air.

Because the amount of air in these pores increases and this increases the resistance in heat transfer. But the assumption that heat transfer is dominant with radiation in this region where is between the heater and porous material can be the most logical approach. Because the contact surface area between the heater and the porous material is very small due to porous surface shape. At the same time, it can be assumed that the natural convection effects of these pores are not dominant parameters in the heat transfer due to the thermal properties of the air.

4. CONCLUSIONS

In this study, the cooling effects of the impinging jet were examined on the surface of the aluminum flat sheet and aluminum close porous materials having different thickness. Behind of both aluminum flat sheet and aluminum close porous materials were placed circular heater. The experimental procedure was carried out at different heater power values and Reynold numbers.

Some important conclusions can be drawn from the experimental study as:

- Maximum local Nu number and temperature are obtained as 153 and 309.1 K for P=3.6 W without porous, when maximum local Nu number and temperature are obtained as 209 and 304 K in the experiment using porous material which thickness of it is 6 mm and P=3.6 W.
- Experimental results showed that when the porous material is not used, the local Nusselt number value is around 150, while the porous material is used, the local Nusselt number value varies between 150 and 250. When the thickness value of the porous material with P = 3.6 W is changed, it can be seen that there is no significant difference between the results obtained for the 6 mm and 8 mm values.
- The results obtained for Re = 2620 and 4192 of thick porous material are better than other results at P = 3.6 W. In the experiments used in 10 mm material, Nu number value is slightly above 250 for P = 3.6 W.
- In experiments where no porous material is used, the maximum local Nu number value is around 250. However, in the experiments where the porous material is used, it is seen that the local Nu number value is changed between 250 and 450 for P = 6.8 W.
- Experiments performed showed that the local Nu number values change from 150 to 350 in experiments for no porous material, while in the experiments where the porous material was used, the local Nu number values change from 250 to 650.
- In the measurements and calculations made in this experiment, the maximum average Nu number value is calculated as 464.06 at Re = 4192, P = 10.5 W. It is observed that for the lowest average Nu number value is obtained at P = 3.6 W and Re = 1048 for without porous material. The lowest average Nu number value is calculated as 94.201.
- It has been observed that the porous material increases the cooling effect. It seems that these porous materials improve heat transfer.

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