EXPERIMENTAL STUDY OF THE EFFECTS OF A VERTICAL CHANNEL ON THE NATURAL CONVECTION OF A HORIZONTAL CYLINDER

by

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In this study, the natural convective flow and heat transfer from a hot horizontal cylinder surrounded by two vertical plates with a negligible thickness was experimentally investigated. These plates act as a channel so that the natural convective flow of the hot cylinder passes through this channel. The flow field was visualized using particle image velocimetry technique to investigate the effect of changing, the width of the channel, and the height of the water free surface on the flow behavior. In each case, by changing the mentioned geometric parameters, flow velocity at the top of the cylinder, temperature of the cylinder surface, volume flow rate of the channel, the structure and location of vortices, and flow pattern inside the channel were studied. The results show that the flow is appropriately formed around the cylinder and inside the channel when both the free surface height above the channel and the channel width are twice the cylinder diameter. Also, the cylinder Nusselt number is increased for the channel with a width ratio of 2, relative to the case without channel around the cylinder.

Key words: *cylinder, particle image velocimetry, natural convection, temperature surface*

Introduction

Various applications of natural convection heat transfer have led researchers to further investigate this phenomenon, and identify factors affecting it. Obviously, the heat transfer increment in applicable circular cylinder case is one of the most important goals of studies on free-convection heat transfer. The cooling of high voltage transmission lines is one of the common applications of natural convection heat transfer around cylinders. Nakamura and Asako [1] investigated the natural convection flow over a horizontal cylinder with an arbitrary cross-section in two states: constant surface temperature and constant heat flux. Haldar [2] conducted a numerical study on laminar free convective air-flow around a horizontal cylinder with external longitudinal wings. Kumar-De and Dalal [3] numerically studied the natural convective flow around a hot cylinder with a rhombus cross-section inside a channel with cold walls. They investigated the effect of repositioning the cylinder, changing the thermal

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boundary conditions, and the ratio of the cylinder cross-section on flow and heat transfer. Their results indicated that the location of the cylinder does not play an important role in heat transfer. Huynh [4] numerically analysed the natural convection cooling of some cylinders placed on the top of a plate at high Rayleigh numbers. His results showed that by reducing the distance between the plate and the cylinders, a flow pattern is produced, through which the heat transfer rate reaches a minimum value. Using the finite element method, Saha *et al*. [5] studied the free convection flow and heat transfer from an insulated cylinder, which was placed in the center of a square channel, whose bottom surface had a constant heat flux. Setting the cylinder inside the channel prevented the free movement of the fluid, which weakened the initial vortices, thus reducing the heat transfer efficiency. Yu *et al*. [6] numerically investigated the unsteady natural convection flow and heat transfer of air from a triangular-cross-section cylinder placed inside a co-axial cylinder. They also investigated the unsteady natural convection of air around a circular cylinder placed inside a triangular cross-section cylinder [7]. Karimi *et al*. [8] numerically simulated the unsteady natural convection flow and heat transfer around two hot horizontal cylinders inside a square chamber with a constant temperature. Their results showed that changes in the average Nusselt number are strongly correlated with the distance between the two cylinders at Rayleigh numbers less than 10000. However, this parameter had no significant impact on heat transfer within the range of Rayleigh numbers in this problem. Rabbani and Talebi [9] used the lattice Boltzmann method to study the natural convection around a cylinder inside a square chamber.

In the meantime, many experimental studies have also been conducted, some of which are introduced in this section. Ashjaei *et al*. [10] used the Mach-Zehnder interferometry method to investigate the effects of Rayleigh numbers and the distance between insulated plates, placed on both sides of a fixed temperature horizontal cylinder with circular and elliptical [11] cross-sections, on the laminar natural convection heat transfer from it. The results showed that increasing the Rayleigh number increases the average Nusselt number and decreases the optimum distance between the plates. They also conducted an experimental study on the steady natural convection heat transfer around a fixed temperature horizontal cylinder placed on the top of an insulated surface. The results showed that increasing the ratio of the distance between the plate and cylinder to its diameter first reduces and then increases the Nusselt number at larger Rayleigh numbers. The average Nusselt number was more sensitive at small Rayleigh numbers because the plate reduced the flow velocity [12]. Karami *et al*. [13] experimentally modeled the natural convection heat transfer from a fixed temperature horizontal cylinder placed inside a vertical insulated channel. Their results showed that for each Rayleigh number, there was an optimal vertical position for the cylinder, where the maximum Nusselt number could be achieved. This optimal position rose with the increased Rayleigh number. Svarc and Dvorak [14] studied the unsteady laminar natural convection flow around a horizontal cylinder confined with a rectangular hole both numerically and experimentally. Their results indicated that the distance between the cylinder and the wall of the rectangular hole would affect the fluid-flow.

Particle Image Velocimetry (PIV) is used as one of the most common methods to analyse fluid-flows in many scientific studies on fluid-flow, including the present study. Grafsronningen *et al*. [15] studied the plume of unsteady natural convection water flow around a horizontal cylinder using the PIV method. He also measured the flow and heat transfer of the unsteady plume above the hot cylinder using the two methods: PIV and laser induced fluorescence, and analytically solved them through a similarity solution [16]. Persoons *et al*. [17] used the PIV method to investigate the heat transfer and natural convective flow of water in the presence of two horizontal cylinders with a constant temperature, which was placed perpendicularly to each other. The aim of this study was to investigate the impact of the buoyancy force, created as a result of heating the lower cylinder, on the local heat transfer of the upper cylinder through changing the distance between the two cylinders and the Rayleigh number. The data obtained from the PIV tests were indicative of the fluctuation of the thermal plume. In addition, the phenomenon of vortex fall occurs near the bottom part of the upper cylinder. The experiment showed that the presence of the second cylinder increased the heat transfer by up to 10%.

The presence of one or two walls around the cylinder changes the parameters corresponding to the flow and heat transfer rate. Marsters [18] conducted an experimental study on the impact of placing two insulated walls around a hot cylinder at several Rayleigh numbers and different distances between the walls. Al-Alusi [19] investigated the natural convection around several horizontal cylinders confined between two vertical walls. The flow was visualized through a laser light sheet. By measuring the heat transfer, a correlation was found for the Nusselt number at different Rayleigh numbers. Saha [20] numerically investigated the natural convection flow from a horizontal cylinder with a square cross-section, which was inside a channel. Moulai *et al.* [21] numerically solved this problem for a dual displacement. Mathis *et al.* [22] reported a heat transfer enhancement due to the presence of two vertical plates around the cylinder which controls the produced vortices above it. Samish and Mahendra [23] parametrically investigated the natural convection heat transfer from an inclined cylinder placed between two vertical plates and presented a relation for the Nusselt number based on the Rayleigh number.

In this study, we experimentally investigated how heat transfer enhancement would occur, as well as the components of natural convection flow around a hot horizontal cylinder inside a vertical channel. The flow around the cylinder is limited by two plates, placed vertically on both sides of the cylinder. These plates act as a channel, and the natural convective flow caused by the hot cylinder flows through this channel. The flow field pattern is obtained using the PIV technique, and the temperature of the cylinder surface and its surrounding area is measured by some thermocouples attached to it. In the analysis of patterns obtained from the PIV technique, we will investigate the flow velocity above the cylinder, the pattern of the flow column above the cylinder, the location and structures of the vortices, and the time of forming a uniform flow inside the channel at different states. The heat transfer coefficient and Nusselt number of the cylinder surface will be obtained at the most suitable water surface height and channel width and will be compared with those in the absence of the channel.

Experimental set-up and measurement systems

As noted at the previous section, the fluid-flow will be studied through the PIV method. The PIV system being used includes a low-divergence DPSS laser with a power of 200 MW, a CCD camera manufactured by SAMSUNG Company with a shooting speed of 25 fps, and a cylindrical lens (in order to convert the laser beam into a plane) with a focal length of 17.63 mm. The laser light sheet is reflected from the fluid by hollow glass spherical particles of 10 and 20 microns in diameter and with a specific density of 1.05. These particles are selected in a way that they have a density close to the water density. The testbed is a Plexiglas container with a cross-section of 20 cm × 30 cm and a height of 30 cm, in which two parallel plates are used to make a channel with dimensions of 12 cm × 18 cm. The thickness of the container wall is 4 mm, and the thickness of the channel plate is 3 mm. A stainless-steel cartridge element of 700 W, with a diameter of 1 cm and a height of 20 cm, is horizontally placed in the middle of the channel. The effective length of this element is 16 cm. Figure 1 shows the schematic of the components of the PIV system and the testbed. The heat flux is generated inside the element using a 220 V AC current. The heat flux value can be controlled by changing the input flow using a 3000 W dimmer.

The temperature is measured at a point away from the cylinder, T_∞, and on its surface, T_s, using two thermocouples of K-type with a precision of 0.1 °C. One thermocouple is placed on the upper surface of the cylinder so that it does not interfere with the flow passing over the cylinder. In all the experiments, the reference temperature is considered to be T_∞ = 27 °C, which is equal to the average temperature of a point at a fixed height from the heater, away from the natural convective flow. Using this value as the reference temperature, Nusselt number values can be easily compared in different states. In fact, with constant heat flux, the increase or decrease of the cylinder temperature represents the decrease or increase of the Nusselt number for the cylinder surface. The PIV system used in this research was validated and used by Taherian *et al.* [24] at low Reynolds numbers. The PIV system, experimental set-up and measurement instruments are also used by Karbasi *et al*. [25] to study the natural convection flow around a heated cylinder with no channel.

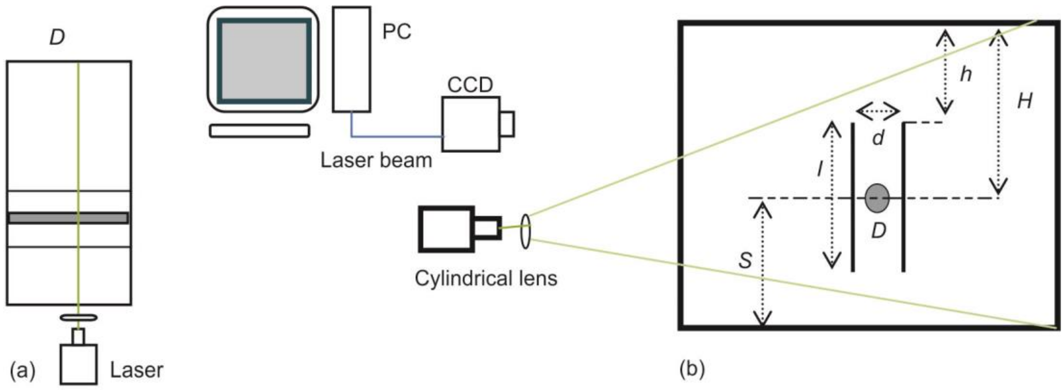

Figure 1.(a) Top view of the schematic of the components of the PIV test and (b) front view of the schematic of the test vessel along with the channel and the heating element in the middle of it

Design of experiments

In this study, the goal is to enhance the natural convection heat transfer by increasing the flow rate passing through the channel. In order to increase the flow rate, two geometric parameters should be evaluated: the water surface height above the cylinder, and the channel width. To this end, first, by keeping the channel width constant, the height to form an appropriate flow above the cylinder was obtained. Then, at this height, some different values for the channel width were selected to find the optimum geometry to increase the flow rate. The experiments were performed at h/D = 0.5, 1, 2, 3, and 5, and d/D = 1.5, 2, 3, and 4. Other parameters including the non-dimensional position (s/D) and length (l/D) of the cylinder were fixed at 8 and 12, respectively.

Data reduction methods

The aim of changing the geometric parameters mentioned in the preceding sections was to achieve a suitable geometry to allow further passing of flow from the cylinder, and finally, to enhance the heat transfer coefficient of the cylinder. The heat transfer rate in a free convection flow can be calculated through the following relation:

$$Q = hA(T_s - T_\infty) \tag{1}$$

The heat flux from the surface is equal to:

$$q" = \frac{Q}{A} \tag{2}$$

where Q [W] is the heat transfer rate, $q"$ [Wm^{-2}] – the heat flux from the surface, h [Wm^{-2}K^{-1}] – the natural convection heat transfer coefficient, A [m^2] – the surface area, and $T_s - T_\infty$ [K] – the temperature difference between the surface and environment. Nusselt number and Rayleigh number can be calculated:

$$\text{Nu} = \frac{hD}{k} \tag{3}$$

$$\text{Ra} = \frac{\text{g}\beta\Delta TD^3}{\alpha\nu} \tag{4}$$

where D is the cylinder diameter, g – the acceleration of gravity, β – the volumetric thermal expansion coefficient, α – the heat diffusivity, k – the heat conduction coefficient, and ν – the kinematic viscosity. For water, the Rayleigh number in the state of a cylinder with no channel as a base state is about 106.

In this experiment, the thermal power of the cylinder heater is constant and equal to 400 W. Taking into account the cylinder diameter, the thermal flux of the heater is equal to:

$$q" = 79577$$

Therefore, the heat transfer coefficient can be calculated:

$$h = \frac{q"}{T_s - T_\infty} \tag{5}$$

The temperature of the cylinder surface, T_s, is presented in the graph of fig. 12, for different channel widths, and as noted, the ambient temperature, T_∞, is equal to 27 °C. The heat transfer coefficient and consequently the total Nusselt number for the cylinder surface can be calculated by substituting the data in eqs. (5) and (3), respectively.

Results of flow visualization

The flow pattern can be observed through imaging the fluid movement due to natural convective flow in each test. Although this pattern undergoes some changes due to changes of the geometric parameters in different states of the tests, the general structure of natural convective flow is the same for all states.

Figure 2 shows the flow pattern at the beginning of the test, forming the flow column, and forming the vortices from the top of the cylinder until exiting the channel at a height-to-diameter ratio of $h/D = 2$. With heating up the cylinder at the beginning of the test, a volume of the fluid starts moving upward in the form of a vertical column. Simultaneously, two small vortices are also formed symmetrically on both sides of this flow column, and along with the flow, move upward inside the channel, fig. 2(a). The size of these vortices depends on the channel width so that the larger the channel width, the bigger the size of the vortices. After passing the vortices through each section of the channel, an upward flow without backflow will be produced at that section, fig. 2(b).

In fig. 2(c), vortices exit the channel. At this moment, because the wall effect has been eliminated, the vortices expand and become larger. The flow column continues moving to reach the water surface, and after colliding with the water surface, it will be divided into two branches, each of which moving toward one side of the container, fig. 2(d). Vortices also continue moving freely in the space below each branch after exiting the top of the channel. Due to the presence of free space outside the channel, these vortices are bigger than those inside the channel, fig. 2(e). The flow branches and vortices gradually become chaotic, fig. 2(f). As the test progresses, and the fluid inside the container becomes hotter, the flow becomes more chaotic, and the flow column disappears. Vortices are also formed chaotically inside the channel. These two issues are further explained in the next section. In either case, after a certain amount of time, the flow inside the channel becomes uniform.

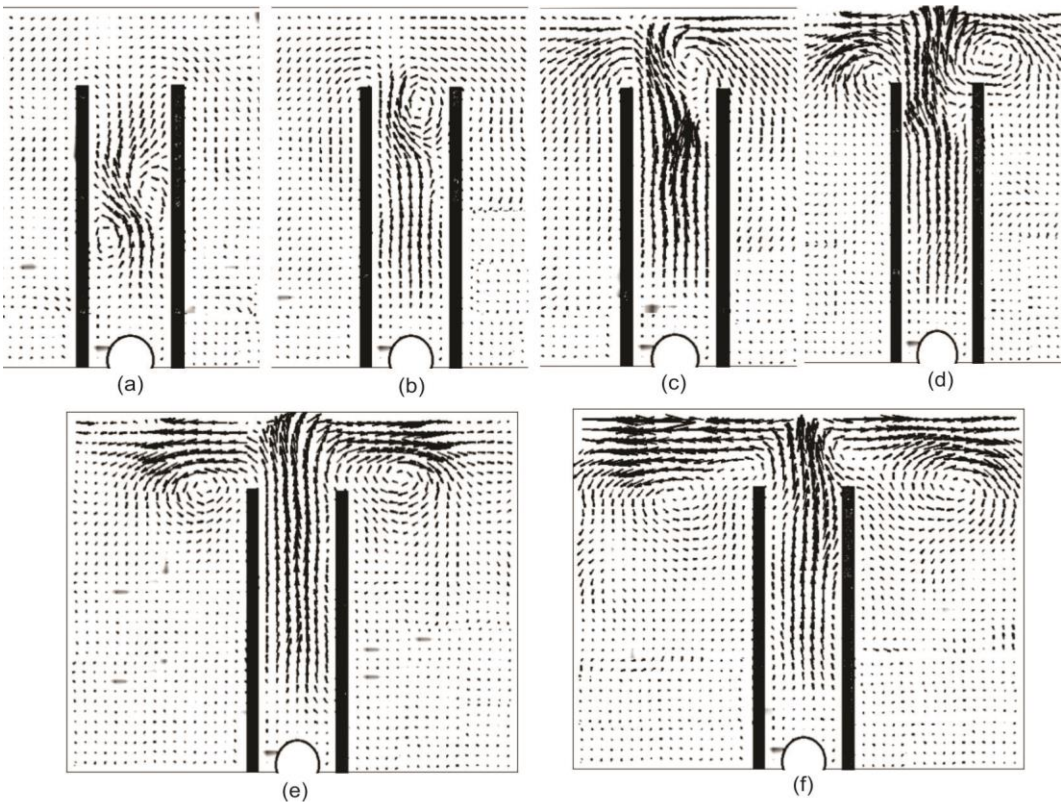

Figure 2. The flow pattern at the beginning of the test, formation of the flow column, and formation of the vortex from the top of the cylinder at different times at a height of h/D = 2; (a) second 12, (b) second 14, (c) second 16, (d) second 18, (e) second 20, and (f) second 22

Effects of water height

The experiments begin by investigating the effect of the water surface height on flow structures. Here, the only variable parameter is in fact the water height. The experiments are performed at five different heights. In each case, flow velocity above the cylinder, the location of vortices, the time of forming uniform flow inside the channel, and flow rate passing through the channel are studied. The water height is the distance from the top of the channel to the water surface, h, and changes to the non-dimensional parameter of h/D whose values are considered equal to 0.5, 1, 2, 3, and 5, respectively. Here, the channel width is constant ($d/D = 2$).

Figure 3 shows the distributions of mean velocity *vs*. time for the flow passing through the channel at five different water surface heights. The mean velocity is calculated at the cross-section 2 cm above the cylinder. By integrating the area below the velocity curve and multiplying it by the area of the channel's outlet ($A_0 = 32$ cm^2), the total volume flow rate of the channel during the test period $\Delta t = 600$ seconds can be determined. Table 1 presents the total volume flow rate *vs*. different water surface heights.

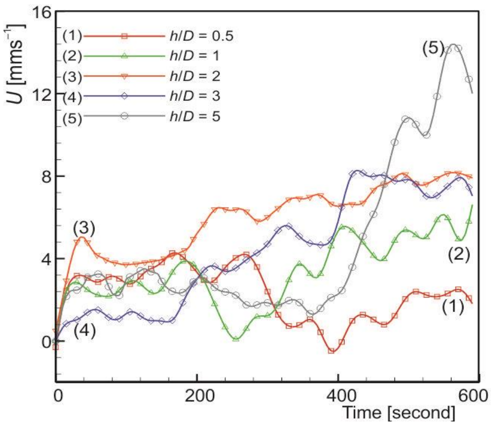

Figure 3. The mean velocity of the flow passing through the channel *vs*. time at five different water surface heights

Table 1. The total volume of the fluid passing through the channel during $\Delta t = 600$ seconds at five different water surface heights

Water surface height, h/D	0.5	1	2	3	5
Total volume [cm^3]	4466	6236	10211	8348	8880

According to tab. 1, the total volume flow rate of the channel is maximum for $h/D = 2$. This is while the total volume flow rate does not change much for $h/D > 2$. As can be seen in fig. 3, at all heights, the flow velocity increases at the beginning of the test ($20 < \Delta t < 40$ seconds). This occurs when the flow column is well-formed above the cylinder. Figure 4 shows this coherent flow column for $h/D = 2$ at $t = 20$ seconds. After that, the flow column becomes chaotic, causing the flow velocity to drop slightly. For instance, in fig. 3, for $h/D = 2$, the flow velocity above the cylinder reaches its lowest value at $t = 100$ seconds, as shown in fig. 5. As the test time passes, vortices are produced alternately inside the channel and are directed out of the channel ($200 < \Delta t < 400$ seconds), which causes some fluctuations in the mean flow velocity curve. But, given that the flow power is increasing, the general trend of the curve in fig. 3 is upward (except at $h/D = 0.5$ and 1). As seen, there is a sharp drop in the mean velocity at $t = 380$ seconds and 250 seconds respectively for $h/D = 0.5$ and 1 that will be discussed later. Figure 6 provides an example of the flow pattern for $h/D = 2$ at $t = 300$ seconds. At all heights, the flow inside the channel needs a certain period of time to be uniform, which is plotted in fig. 7. Figure 8 shows the uniform flow pattern for $h/D = 2$ at $t = 500$ seconds. When the flow inside the channel becomes uniform, because no vortices are created inside the channel, the flow will experience an increase in velocity. The big jump in the mean velocity curve of fig. 3 for $h/D = 5$, is associated with this phenomenon. At $h/D = 5$, although the uniform flow takes longer to be formed, it is more powerful when forming. Figure 9 shows a powerful uniform flow for $h/D = 5$ at $t = 540$ seconds.

When the water surface height, h, is small, this uniform flow is weak and does not have the power to get out from the top of the channel. Whereas at high water surface heights, this flow is well-formed, and will increase the flow velocity of the channel. As the height increases, the power of this uniform flow increases, but the time of its occurrence is delayed too, in a way that in the case of long-term cooling, this height will be efficient.

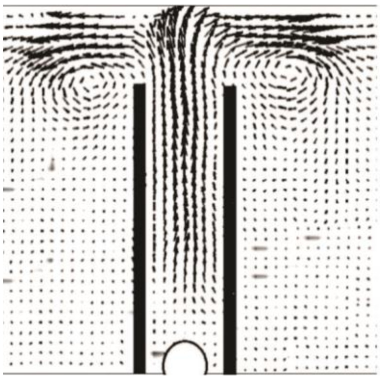

Figure 4. The coherent flow column for *h*/*D* = 2 at *t* = 20 seconds

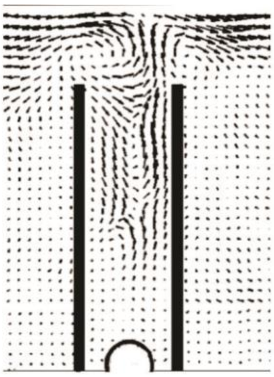

Figure 5. Chaos in the flow column for *h*/*D* = 2 at *t* = 100 seconds

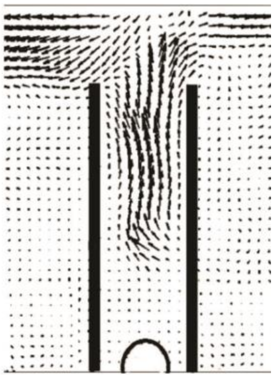

Figure 6. The flow pattern at for *h*/*D* = 2 at *t* = 300 seconds

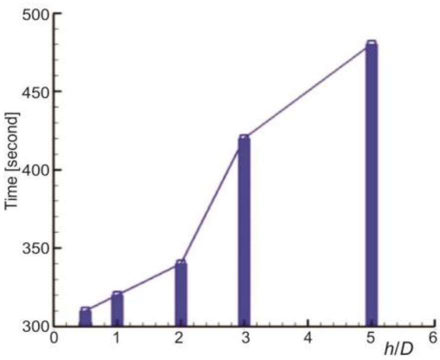

Figure 7. Time for the flow inside the channel to reach the uniform state at different water heights

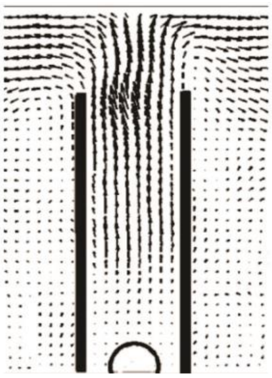

Figure 8. The uniform flow for *h*/*D* = 2 at *t* = 500 seconds

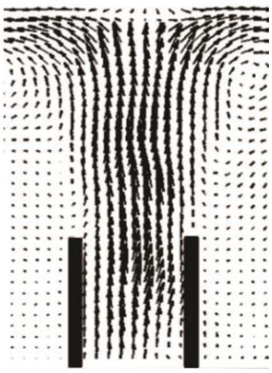

Figure 9. The formation of a uniform flow inside the channel for *h*/*D* = 5 at *t* = 540 seconds

Depending on the water surface height, vortices will form inside or outside the channel. In fig. 10, as the water surface height increases, the location of forming the vortices can be seen.

According to fig. 10, in all cases, the location of forming the vortices is almost 1 cm below the water surface. Therefore, at $h/D = 0.5$, these vortices fall inside the channel, at $h/D = 1$, at the upper edge of the channel, and for the rest of them, outside the channel. The experiments show that at $h/D = 0.5$ due to the limited distance above the channel, the vortices cannot exit the channel and disappear inside the channel, and again new vortices will be produced. This makes the fluid above the cylinder heat up, which causes problems with the natural convection phenomenon. As a result, the flow velocity slows down so that the flow rapidly goes toward boiling. In the case of $h/D = 0.5$, a sharp drop in flow velocity can be seen at $t = 380$ seconds on the mean velocity curve of fig. 3. Also, at $h/D = 1$, because vortices form at the upper edge of the channel and cause a disturbance for passing the flow, there is a drop-in velocity at t = 250 seconds on the velocity curve of fig. 3. Figures 10(a) and 10(b) show how the vortices on the flow path cause a drop-in velocity for h/D = 0.5 and h/D = 1. By increasing the height of the water surface, the limitation of trapping vortices inside the channel is removed.

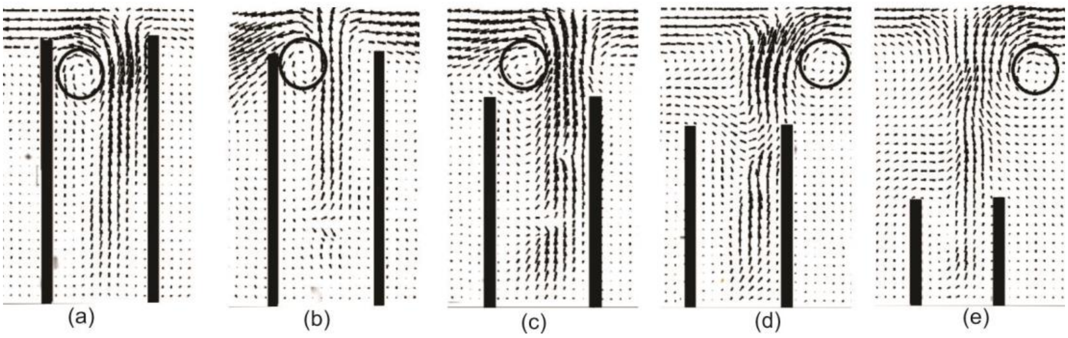

Figure 10. The location of the formation of vortices at different water surface heights; (a) h/D = 0.5, (b) h/D = 1, (c) h/D = 2, (d) h/D = 3, and (e) h/D = 5

According to the aforementioned results, at h/D = 2, the flow velocity above the cylinder is appropriate during the test time and makes the total volume flow rate of the channel reaches its highest value, the vortices from outside the channel, and the uniform flow form appropriately inside the channel.

Effects of channel width

In this section, the only variable parameter is the ratio of channel width to cylinder diameter, which takes the following values: d/D = 1.5, 2, 3, and 4, respectively while the other parameters are considered constant (h/D = 2 and l/D = 12).

The distributions of flow velocity and cylinder surface temperature *vs*. time are respectively shown in figs. 11 and 12 at four different channel widths. Also, in tab. 2, the total volume flow rate of the channel is calculated for these four states.

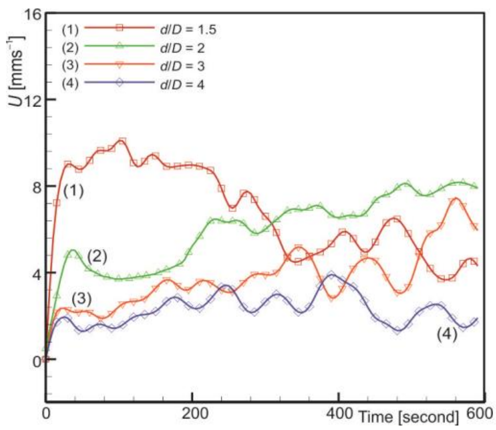

Figure 11. The flow velocity distribution *vs*. time at four different channel widths

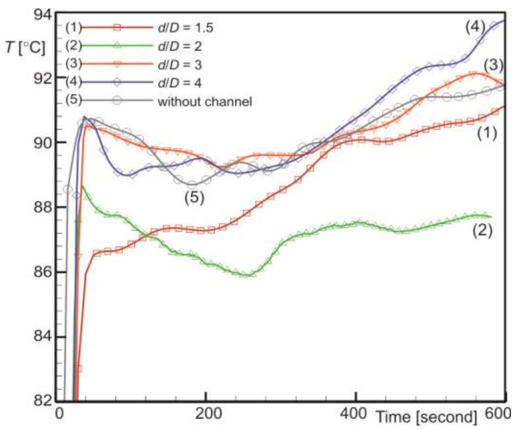

Figure 12. The temperature distribution of the cylinder surface at four different channel widths and at the absence of the channel

The results of tab. 2 show that the effect of the channel width on the total volume flow rate of the channel is not as great as the effect of the water surface height. Therefore, it will be concluded that the channel width should be selected in a way that the flow column can easily move upward inside the channel.

Table 2 .The total volume flow rate of the channel during Δt = 600 seconds at four different channel widths

Channel width, *d*/*D*	1.5	2	3	4
Total volume [cm^3]	9797	10211	10743	8651

In this section, changing the channel width changes the area of the channel outlet, and a mere increase or decrease in the volume flow rate is not a proper criterion for evaluating the enhanced heat transfer. For instance, the total volume flow rate is the same for d/D = 2 and d/D = 3, while the velocity values at d/D =2 are higher than the other case. As shown in fig. 12, the temperature of the cylinder surface for d/D =2 is lower than that for the rest of the cases. It is noticeable that the flow velocity for d/D = 1.5 is greater than that for the rest of the cases until t = 300 seconds while after that, due to the small channel width and the flow blockage near the cylinder, the flow velocity decreases rapidly so that the temperature of the cylinder surface increases. In fact, a certain volume flow rate has to pass through the small width of the channel until t = 300 seconds, which causes the flow to pass over the cylinder at a higher velocity, and due to this high velocity, the cylinder surface temperature is low at the early stages of the test, fig. 12. In the previous section which investigated the water surface height, the channel width was considered constant and equal to d/D = 2. Hence, the further explanation regarding the d/D = 2 state is the same as the explanation given in the previous section. The most important factor influencing the trend of the velocity curve in the d/D = 3 and d/D = 4 states, fig. 11, is the location of the formation of vortices, which will be explained later.

According to fig. 12, it can generally be said that when the flow passes over the cylinder at a higher velocity, heat transfer is carried out better, and the lower will be the temperature of the cylinder surface. But it should also be noted that the temperature of the fluid passing over the cylinder, is also very important in the cooling of the cylinder surface. According to fig. 12, at d/D = 1.5, the temperature of the cylinder surface is low until t = 300 seconds, until which the flow rapidly passes over the cylinder. During the whole time of the test, for d/D = 2, the temperature of the cylinder surface is lower than that in the other states (except during the first hundred seconds of the test, during which the temperature of the cylinder surface is lower in the d/D = 1.5 state). At t = 250 seconds, this temperature reaches its lowest limit. If you pay attention to the flow velocity curve, you can see that this time corresponds to the time when the flow velocity is at a high level. From this time on, regardless of the trend on the flow velocity curve, the temperature of the cylinder surface has an increasing trend in all states. This is because the flow velocity has a growing trend at some moments after the middle of the experiment, while it is no longer as cool as that at the beginning of the experiment. It will decrease the heat transfer rate and will have a lower effect in decreasing the temperature of the cylinder surface.

Figure 13 shows the location of vortices formation at different channel widths. It should be noted that the locations of vortices are compared in different states at a time when these vortices have the highest stability during the test. At d/D = 1.5, vortices form close to the cylinder so that they do not allow the formation of a high-power flow column from the very beginning. Along the channel and above it, not only no vortices form, but also if forming, they will be small and will be quickly directed out of the channel. At d/D = 2, vortices from outside the channel at its upper edge, and vortices forming inside the channel are also directed out of the channel and do not cause chaos in the flow column inside the channel. In addition, vortices form above the channel at $d/D = 3$, and inside the channel at $d/D = 4$. Figure 11 shows that in both states of $d/D = 3$ and $d/D = 4$, the flow velocity curve does not rise considerably over time, and only follows a fluctuating trend. This fluctuating is due to the locations of the formation of vortices in these two states which prevent the formation of an appropriate flow.

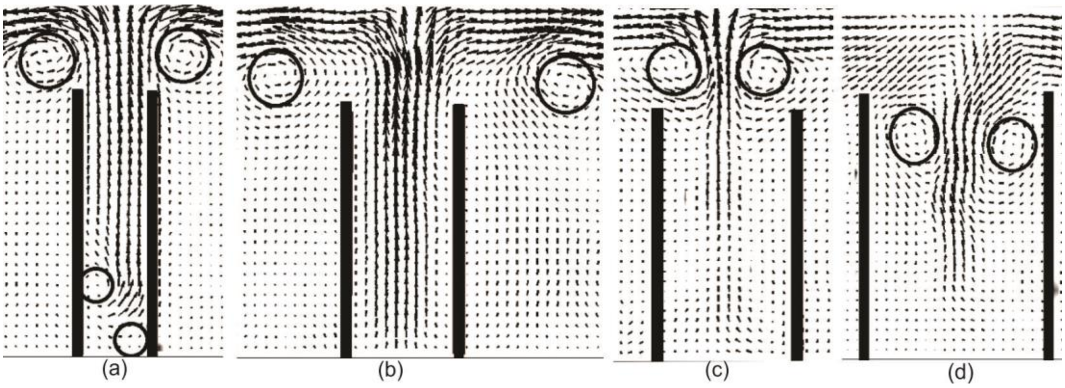

Figure 13. The locations of vortices forming and their sizes as the channel width changes; (a) $d/D = 1.5$, (b) $d/D = 2$, (c) $d/D = 3$, and (d) $d/D = 4$

With the investigations being done, it is found out that an appropriate ratio of the width to the cylinder diameter, d/D, can be determined to increase the flow velocity from the cylinder, and reduce the cylinder temperature. According to fig. 13, in the small channel width ($d/D = 1.5$), the formation of small vortices inside the channel causes obstruction in the flow. When the channel width is big ($d/D = 4$), very large vortices from inside the channel due to the sufficient space inside it. In either case, these vortices reduce the flow passing through the channel. Figure 14 shows the time when the flow inside the channel becomes uniform. It should be noted that when the channel width exceeds $d/D = 3$, the uniform flow will no longer form inside the channel during the test. Figure 15 shows the flow pattern at $d/D = 4$ at $t = 540$ seconds as well as the non-formation of the uniform flow.

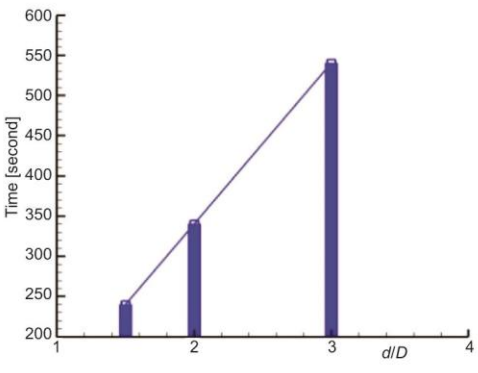

Figure 14. Time for the flow to reach the uniform state by changing the channel width

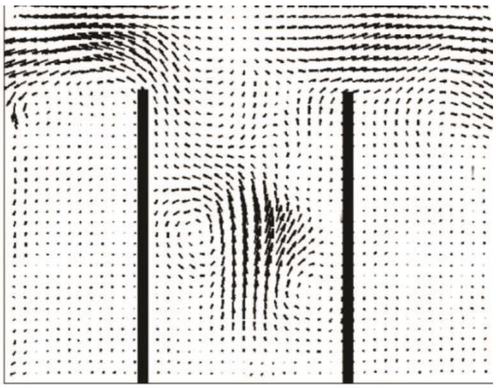

Figure 15. Large vortices inside the channel at $t = 540$ seconds for $d/D = 4$, and non-formation of the uniform flow

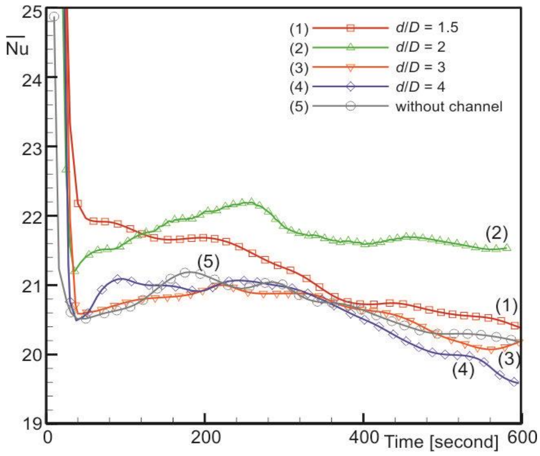

Figure 16. The Nusselt number of the cylinder surface *vs.* time, for four different channel widths

Given the investigations carried out in this section, and according to the velocity and temperature curves in figs. 11 and 12, the channel width $d/D = 2$ is the best geometry for passing the flow over the cylinder. With this width, the flow forms well around the cylinder and the temperature of the cylinder surface will also be lower than that at the other channel widths.

Results of heat transfer coefficient

Figure 16 presents the Nusselt number of the cylinder surface *vs.* time, for four different channel widths.

Table 3. The mean Nusselt number for the cylinder surface during the whole test, Δt = 600 seconds

Parameter \ State	$\overline{\text{Nu}}$
Without a channel	19.37
$d/D = 1.5$	19.85
$d/D = 2$	20.37
$d/D = 3$	19.34
$d/D = 4$	19.28

As clear in fig. 16, the Nusselt number is greater for the $d/D = 2$ state than in the rest of the states during the whole test, except during the first hundred seconds of the test in the $d/D = 1.5$ state. Table 3 provides the mean free convection Nusselt number for the cylinder surface during the whole test, $\Delta t = 600$ seconds, for different channel widths as well as in the state of a cylinder with no channel according to:

$$\overline{\text{Nu}} = \frac{\bar{h}D}{k} \tag{6}$$

As it can be seen in fig. 16, the Nusselt number of the cylinder surface have their highest values in the state of $d/D = 2$, and have their lowest values in the state of $d/D = 4$. The Nusselt number has increased in the state of $d/D = 2$, relative to the state with no channel around the cylinder. This increase is indicative of the effect of the presence of a channel on heat transfer enhancement.

Conclusion

In this study, we investigated the flow pattern and the free convection heat transfer rate around a hot horizontal cylinder inside a vertical channel, and also investigated the changes in the free convection heat transfer rate from the cylinder surface as the two parameters: the fluid height and the channel width were changing. Using the PIV technique, we obtained the flow pattern at different water surface heights and for different channel widths and then compared them with each other. We also obtained the temperature of the cylinder surface for different channel widths using a thermocouple. Our investigations showed that with the cylindrical heater heating up, the fluid began to move upward in the middle of the channel in the form of a flow column, and when colliding with the water surface, it divided into two branches. When the water surface height above the cylinder was small, the vortices formed inside the channel, and when the water surface height above the cylinder increased, the vortices formed outside the channel. The formation of vortices inside the channel decreased the velocity of the flow passing over the cylinder. In addition, with the channel width increasing, sufficient space was created to form the vortex inside the channel, which reduced the velocity of the flow passing through the channel. Moreover, the reduction in the channel width caused obstruction in the position of the cylinder inside the channel. The results showed that in the state where the ratio of the water surface height above the channel to the cylinder diameter was $h/D = 2$ and the ratio of channel width to the cylinder diameter was $d/D = 2$, the flow formed well around the cylinder and inside the channel. In addition, the Nusselt number and heat transfer coefficient increased in the state of a channel with a width ratio of $d/D = 2$, relative to the state, where there was no channel around the cylinder. In addition to heat transfer rate increment, the flow patterns are totally different from a simple case, that shows the effect of the presence of walls, and explain how the channel change the velocity, temperature, and heat transfer rate.

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