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EXPERIMENTAL INVESTIGATION ON FLOW THROUGH A CONFINED RECTANGULAR CHANNEL MOUNTED WITH SQUARE BLOCKS

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Abstract

Study on separated flow and step flow is subject of interest for many years for its wide industrial applications like cooling of electronic devices, heat exchangers, gas turbine components and other thermal equipments. Present experimental investigation is to report the influence of the block over rectangular channel in confined environment. Size of recirculation vortex, center of recirculation vortex for various Reynolds number with center to center distance between the blocks in the stream wise direction of the flow (L_x/L_y ratio) equal to 2, are the parameters reported when water is used as the working fluid. Outcome of this experimental study shows that, the size of the vortex increases with the increase of Reynolds number and the center of the vortex shifts in the direction of flow downstream of the blocks. Reynolds number considered for this study ranges from 800 to 1500 with a step of 100. Flow visualisation for the range of Reynolds number is presented.

Keywords: Channel flow, Flow over blocks, Flow visualisation, Reynolds number, Vortex center.

1. Introduction

Flow over block is common in many industrial applications for instance cooling of electronic components, solar collectors, chemical processing equipments, etc. Flow over heated blocks has been a situation which simulates the electronic components mounted on a printed circuit board. The primary concern in the study of electronic packaging is to enhance the convective cooling of chips. Sewatkar et al. [1] have

Nomenclatures

D_h	Hydraulic diameter, m
H	Height of the channel, mm
h	Height of the block, mm
L	Length of the channel, m
L_x	Stream wise direction center to center distance between blocks, cm
L_y	Transverse direction center to center distance between blocks, cm
N_u	Nusselt number
Re	Reynolds number
V	Mean velocity of flow, ms^{-1}
W	Width of the channel, mm
X_1	Reattachment length, mm
x	Stream wise direction (subscript)
y	Transverse direction (subscript)

Greek Symbols

v	Kinematic viscosity of water, m^2/s

Abbreviations

CCD	Charge couple device

studied numerically the effect of Reynolds number and space between rows of square cylinders mounted on a rectangular channel as two dimensional problems. They have presented that the critical Reynolds number for the onset of vortex shedding increases with increase in gap ratio. The Reynolds number is found to have a strong effect on the flow especially at s/d with 3.0 and 4.0

Numerical study on plane wall jet over backward facing step is studied in detail and reported by Kanna and Das [2-4]. The hydrodynamic numerical study is carried out to find the effect step length and thickness in connection with Reynolds number. The nonlinear behaviour of recirculation eddy and its size is presented in [2]. Further to investigate the heat transfer from the geometry is studied with the effect of flow and geometry properties. They found that the peak Nusselt is shifted downstream to the reattachment length [3]. Direct Numerical Simulation technique has been used to study the flow through a channel in the presence of an obstruction by Senthil et al. [5]. They compared the results with experimental results for Re = 4000 and phenomenon of reverse flow is reported in detail. They have found that the reverse flow is due to the reduced pressure by the obstruction introduced at the entrance of the channel. Finally they have concluded that reverse flow may be slightly decreased by increasing the width of the channel.

Flow under backward facing step is subject of interest for many researchers. Armaly et al. [6] carried numerical as well as experimental study for laminar flow and published results for hydrodynamics and heat transfer. Recently flow over a rectangular porous block placed in a channel is studied numerically by Shuja and Yilbas [7]. Further Shuja et al. [8] investigated that effect of block orientation and aspect ratios on the heat transfer rates.

Garimella et al. [9], from the experimental investigation have found that, the transition is strongly depending on the array geometry and flow rate. For all heights of the channel it is explored that, the transition takes place at the same mean velocity. Experimental results of the thermal and hydraulic behaviour of silicon based low aspect ratio micro pin fin cold plate under cross flow conditions are reported by Ravi et al. [10]. Circular and square shapes of the pin fin are considered for experimentation and water is used as a working fluid.

Experiments are conducted by Meinders and Hanjalic [11] and reported the influence of blocks arrangement in in-line and staggered position. Reynolds number equals to 3900, span wise distance *Sz/H* with 0.5, 1, 1.5, 2 and 3, and stream wise distance *Sx/H* with 2, 4 and 8 are considered for the turbulent study. In case of staggered arrangement of the blocks they have found that, for small values of *Sx/H* and *Sz/H* significant asymmetric flow structures are observed. Numerical investigation on unsteady laminar flow over plane channel with two square blocks mounted side by side has been conducted and reported by Alvaro and Ronald [12]. They have presented that, heat transfer and pressure drop strongly depend on the transverse distance between the blocks.

Sushanta et al. [13] investigated experimentally the flow past a square cylinder placed at an angle to the incoming flow using particle image velocimetry, hot wire anemometry, and flow visualisation. The Reynolds number based on cylinder size and the average incoming velocity is set equal to 410. They presented and discussed about the flow visualisation images in the near wake of the cylinder. They found that the shape and size of the recirculation bubble downstream of the cylinder are strong functions of orientation.

The heat sinks or cold plates of an electronic enclosure are usually cooled by water [14] by passing it through channels made for this purpose or through tubes attached to the cold plate. High heat removal rates can be achieved by circulating water through these channels or tubes. In high-performance systems, a refrigerant can be used in place of water to keep the temperature of the heat sink at subzero temperatures and thus reduce the junction temperatures of the electronic components proportionately.

Dao et al. [15] experimentally investigated the laminar and transition opposing mixed convection when the air flow is in the entrance region through a rectangular duct. The drop in pressure is measured under different air flow rates, convective heat fluxes and inclination angles, with the maximum value less than 6.0 Pa. They calculated the friction factors and analysed under different Reynolds numbers, Grashof numbers and inclination angles. They reported that, the pressure drops increased with the mean air velocity, and the friction factors showed different characteristics when the Reynolds numbers are larger or smaller than 1500. Finally, the correlations of friction factors were fitted considering the influences of Reynolds number, Grashof number, inclination angle and length to diameter ratio, which fitted the experimental data with the deviations less than $\pm$10.0%.

An experimental investigation has been carried out to study heat transfer and friction coefficient by dimpled surface by Sandeep et al. [16] in a rectangular channel with aspect ratio of 4.1. Reynolds number based on hydraulic diameter is chosen from 10000 to 40000. The ratios of dimple depth to dimple print diameter is varied from 0.02 to 0.04 to provide evidence on the impacts of dimple depth and compared the results with smooth plate of similar situation. It is presented that for all Reynolds number, depth increases from 0.2 to 0.3, Nusselt number and thermal performance increases and then subsequently when depth increase from 0.3 to 0.4 Nusselt number and thermal performance decreases. They found that the above said variation in thermal performance and Nusselt number is due to increase in strength and intensity of vortices and associated secondary flows expelled from the dimples.

Comparison of Experimental and Numerical results are reported by Venkatachalapathy and Udayakumar [17] on mixed convection heat transfer from a rectangular enclosure having an array of heat sources mounted on the flow path. Results show that the heat transfer is more on the blocks near the wall enclosure compared to those in the inner side. Reynolds numbers considered for this study are 900, 1800 and 3600.

From the literatures, there are many studies carried out on flow over solid blocks and they are limited on either more generic system specific results or limited to two dimensional case. Very few experimental results are presented and air is used as working fluid. The effect of arrangement of blocks in Zig Zag manner mounted over flat plate and water as working fluid is not carried out. This supposed to reflect the real nature of the problem which invites attention for this study. Since water is having decent thermal properties compare to air, an attempt has been taken to use water as working fluid for this experimental study.

2. Experimental Setup

The schematic view of the whole experimental facility is shown in the Fig. 1. The experimental setup consists of three tanks. The size of the main tank is 1.50 m × 0.5 m × 0.30 m, supply tank size of 0.5 m × 0.5 m × 0.75 m and a collecting tank of size 0.5 m × 0.5 m × 0.75 m. Self-priming centrifugal pump of 0.5 hp is used to circulate the working fluid. The channel is divided into three segments namely upstream side of the test section, test section and downstream side of the test section. Length of the upstream side and downstream side of the test section are equal and rectangular cross section of size 3.8 cm × 1.7 cm. Total length of the channel including the test section is 3.283 m in which 1.5 m upstream side and 1.5 m downstream side. To achieve the fully developed flow and to maintain laminar flow throughout the length of the channel, ratio of length of the channel to height of the channel (L/H ratio) maintained is 193 [6]. The overhead reservoir provides a constant head for the gravity fed water supply to the rectangular channel. Desired Reynolds number is achieved by regulating the control valve provided between the channel and supply tank. Water exit from the rectangular channel is collected in the collecting tank and the same water is pumped back into the overhead reservoir. Control valve provided at the delivery pipe of the pump is used to regulate the flow of water to overhead tank to maintain constant head. Two pressure tapings one at the inlet of the test section and another at the outlet of the test section respectively, are used to find out the pressure drop in the test section between the blocks. For flow visualisation high end PC and a SONY CCD camera of resolution 1024 × 768 pixels is used to record the flow and post processing.

A stand of height 1.5 meters is made which has a hook at its top. Dye-solution used is Crystal Violet paint which is available in liquid form for medical applications and the concentration of the dye solution is high so that it takes time to blend with water. The solution is kept in a saline bottle and is hung from the hook. The dye injection system consists of a hose pipe of 2 mm internal diameter and outer diameter equal to 3 mm. A Becket & Dickinson Precision Glide Hypodermic Needle (OD = 0.89) is placed at the mouth of the hose pipe.

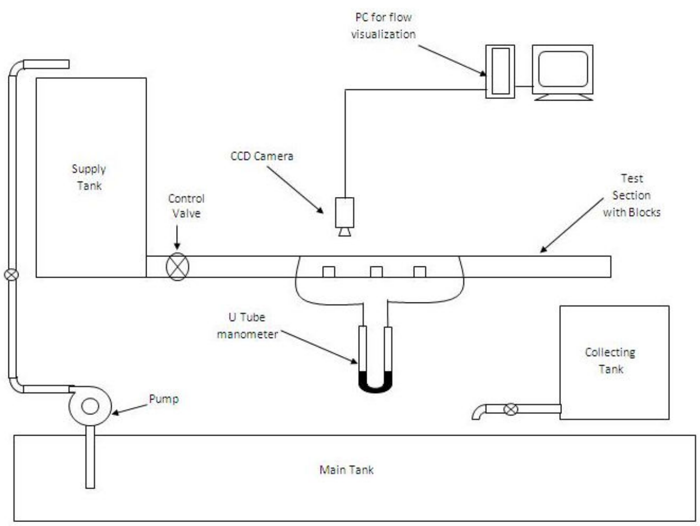


Fig. 1. Schematic diagram of experimental setup.

2.1. Test section

The location of the test section is between the upstream side and downstream side of the channel. Dimensions of the test section are 28.3 cm × 3.8 cm × 1.7 cm. Bottom wall of the test section made up of aluminium and remaining sides of the test section are made up of plain glass of thickness equal to the wall thickness of the channel. Four numbers of square blocks are mounted on the bottom wall of the test section in a zig zag manner. Location of the first square block is placed at a distance of 1.9 cm from the inlet of the test section. The distance between two square blocks is 3.8 cm in x-direction L_x and 1.9 cm in y-direction L_y so as to maintain the L_x/L_y equals to two. Size of the square block employed for this study is 1.6 cm × 1.6 cm × 0.9 cm so that the blockage ratio height of the block to the height of the channel h/H equal to 0.50. The schematic diagram of the test section is shown in Fig. 2.

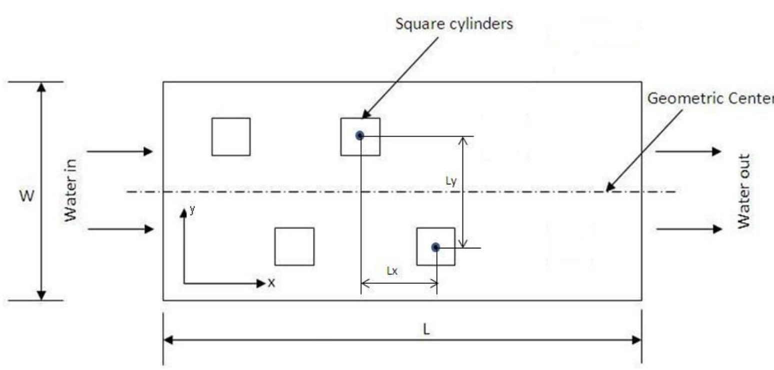


Fig. 2. Top view of the test section.

The assumption made during this study is two-dimensional, steady and incompressible flow.

2.2. Parameters affecting flow field

In the present experimental work the flow field variation has been investigated over the following parameters. For different Reynolds number, by keeping L_x/L_y ratio equal to two reattachment length, center of the vortex and the size of the vortex has the influence on the fluid dynamics.

a) L_x/L_y Ratio

Where L_x is the distance between the centers of the blocks in stream wise direction of the flow and L_y is the center to center distance between the blocks in span wise direction of the flow. The span wise direction between the blocks is 19 mm and the stream wise direction is 38 mm. The L_x/L_y ratio calculated is 2.

b) Reynolds Number (Re)

On varying the Reynolds number from 800 to 1500 with a step of 100, i.e., 800, 900, 1000, etc., the respective flow fields are obtained. The reason for taking such a low Reynolds Number is that the introduction of block would render the flow may turn into turbulent, if the Reynolds Number is more than 1500.

c) Block size

Four number of square block of size 16 mm × 16 mm × 9 mm is fixed on the bottom plate. For all the blocks the L_x/L_y ratio is kept constant.

2.3. Experimental procedure

Water stored in the overhead tank is allowed to flow through the rectangular channel and the flow rate is controlled by the gate valve provided on the upstream side of the test section. The head in the overhead tank is maintained constant by adjusting the gate valve available between the pump and the delivery pipe to the overhead tank. The time taken to reach the steady state is between 80 to 90 minutes. After reaching steady flow through the channel, the time taken for collecting 5 cm head of water in the collecting tank is measured to ensure the Reynolds number of the flow. The uncertainty calculated for the Reynolds number is 3.46% as reported by Holman [18]. For every Reynolds number five readings are taken and the average value of flow rate is used to calculate the Reynolds number using the following expression given in Eq. (1) which is used by Kadir et al. [19].

$$\mathrm{Re} = \frac{VD_h}{\nu} \tag{1}$$

Nearly 400 images of the flow, recorded for 3 minutes by a SONY 12 Mega pixel camera with 4x zoom is take for finding the reattachment and separation point. The maximum field of view of the camera is set to 150 mm to cover three blocks from the entrance of the test section. Crystal Violet paint is used for flow visualisation. Approximately the flow velocity of the dye is maintained equal to the flow velocity of the working fluid. Flow of dye is adjusted by varying the vertical position of the dye container. Post processing of the captured images is carried out using Get Data Graph Digitizer version 2.24.

3. Results and Discussions

Water is used as working fluid, having kinematic viscosity of 8.351×10^{-7} m^2/s. at room temperature 30°C. Experiments are conducted for Reynolds numbers ranges from 800 to 1800. Experiment is started with Re = 800, since the variation in the Reynolds number is very high for slight movement of the flow control valve. Due to this step of 100 Reynolds number is considered. Since the cross section of the test section is 3.8 cm × 1.7 cm, fully developed flow is obtained at the downstream of the test section for the Reynolds number 800 only.

Figure 3 shows the flow pattern, reattachment length, and formation of vortex on the downstream side of the blocks. From the Figs. 3(a) to (h) for Reynolds number 800 to 1500 the flow patterns are visible and for the Reynolds number above 1500 due to the transition in the flow it is difficult to find the flow patterns. The dye is also starts dissolving rapidly due to the transition in the flow before it reaches the second block.

Table 1 shows the reattachment length obtained for Reynolds number ranges from 800 to 1500. Reattachment length is calculated as a non-dimensional number, i.e., X_l/h. Where X_l is Reattachment length in mm and h is the height of the block.

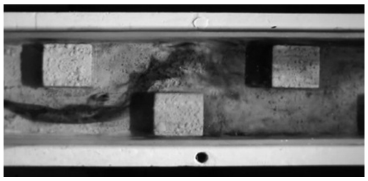
From Table 1 and Fig. 4 the dependency of the Reynolds number and reattachment length is observed that, increasing in Reynolds number increases the reattachment length. From Fig. 4, the reattachment length drastically increases with increases Reynolds number up to 1000 and above Re = 1000 the increase in reattachment length is approximately 8.3% as that of the previous Results. The flow starts separating due to the sharp edges present in the blocks. This effect is so called edge effect [19]. As the inertia force grows the recirculation size increases which in turn increase in reattachment is detected.

Table 2 discloses the center of vortex with respect to the entrance of the test section. Center of the vortex is calculated in graphical method. The image of the flow for Reynolds number ranging from 800 to 1500 is captured using SONY 12 Mega pixel camera with 4x zoom. Nearly 400 images for each Reynolds number are recorded. Get Data Graph Digitizer version 2.24 Software is used to get the center of the vortex from the image of the flow for each Reynolds number.

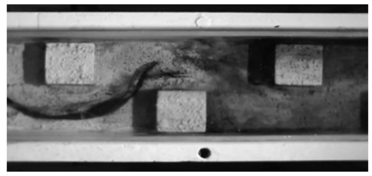
From Table 2 it is observed that the center of vortex in x direction is increasing in the increase in of Reynolds number. The vortex is formed in the downstream side of the blocks. The data obtained are with respect to the second block for L_x/L_y ratio is equal to two. The center of the vortex in the direction of the flow shifts downstream side of the flow. It is interesting to note that the center of the vortex in the span wise direction of the flow is wavering. This shows the stability of the vertex in the transverse direction of the flow. The lack of stability of the flow in transverse direction of the flow is due to the increase in inertia force.

a) Reynolds number 800

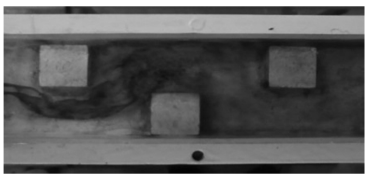
(b) Reynolds number 900



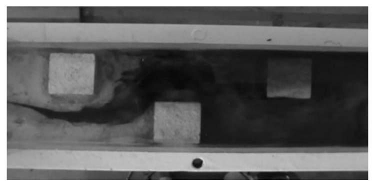
(c) Reynolds number1000



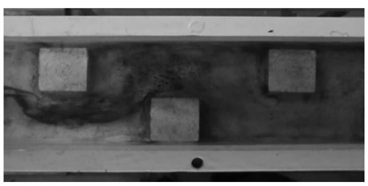
(d) Reynolds number1100



(e) Reynolds number 1200

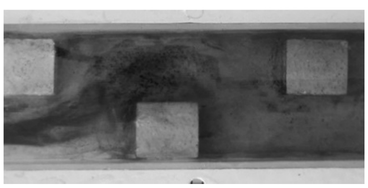


(f) Reynolds number 1300

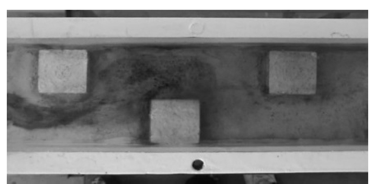


(g) Reynolds number 1400

(h) Reynolds number 1500



(i) Reynolds number 1600



(j) Reynolds number 1700

(k) Reynolds number 1800

Fig. 3. Visualisation of flow for $L_x/L_y = 2$.

Table 1. Reattachment length for various Reynolds numbers.

Re	X_1/h
800	0.900
900	1.203
1000	1.351
1100	1.372
1200	1.413
1300	1.454
1400	1.524
1500	1.662

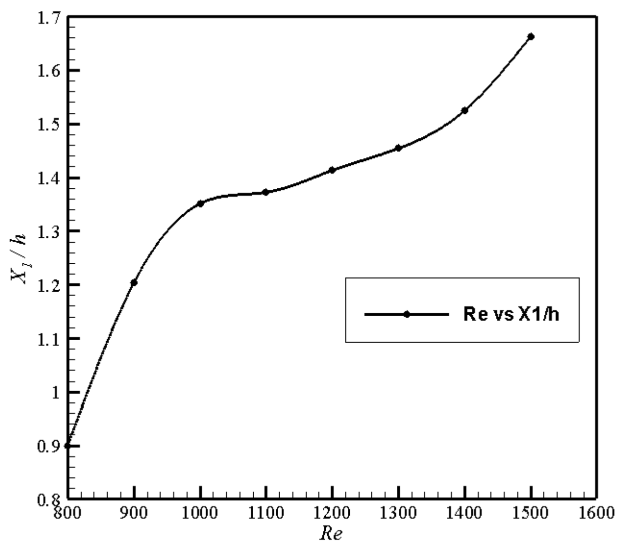


Fig. 4. Reynolds number vs. reattachment length.

Table 2. Center of vortex for $L_x/L_y = 2$ for various Reynolds number.

Re	Vortex Center in mm *x* Coordinate in mm	*y* Coordinate in mm
800	55.824	8.286
900	56.088	9.032
1000	56.308	8.871
1100	57.273	9.154
1200	57.315	9.195
1300	58.035	8.173
1400	58.420	8.749
1500	59.028	7.990

From Table 3, on increase in the Reynolds number, the size of the vortex in x direction is also increases. Increase in inertia force is responsible for the recirculation between the blocks. The presence of edges in the square block increases the recirculation region downstream of the blocks. The effect of recirculation between the blocks enhances the size of the vortex in the stream wise direction of the flow [6]. The same pattern is also followed for size of the vortex in y direction whereas the interaction of the edge effect is observed minimum in the span wise direction of the flow.

Table 3. Size of vortex in *x* direction and in *y* direction.

Re	Size of vortex along *x* direction	Size of vortex along *y* direction
800	5.447	8.784
900	7.220	13.064
1000	8.232	13.848
1100	8.420	15.070
1200	8.406	14.181
1300	8.802	13.596
1400	9.152	14.303
1500	10.548	18.178

4. Conclusions

This experimental study leads to the following conclusions. Experimental investigation on effect of the square block mounted on the flat plate is carried out for Reynolds number ranges from 800 to 1500. The reattachment length, size of the vortex and the center of vortex in x direction and y direction are reported for the above said Reynolds number. The results show that, increasing in Reynolds number there is an increase in reattachment length. For the same Reynolds number range the flow is greatly affected by the presence of block on the flow path.

In heat transfer problems the peak Nusselt Number (N_u) is obtained at the reattachment point. According to the place where more heat transfer is required the position of the reattachment point may also be shifted by positioning the blocks. Present study results, non-dimensional number (Re) Reynolds number is involved, it can be applicable for similar fluids with higher thermal conductivities.

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