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# Turbulent Flow Characteristics in Internally Grooved Pipe

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**ABSTRACT**

Turbulent flow characteristics in internally grooved pipe have been investigated experimentally. The observation has been done at number of groove of 24, 32 and smooth pipe used as comparison. The results indicate that in the 24 groove, vortices of lesser size than the groove width thereby causing the flow to rotate, increasing both radial velocity and pressure drop. Whereas, in the 32-groove, the vortices diameter is larger than the groove width so that the fluid did not rotate which reduced radial velocity and pressure drop. In this study, the critical conditions were estimated from the time the fluid rotation actually commenced in the smooth pipe (no grooves) which was then correlated to both the 24 groove and 32 groove pipes. Critical conditions occurred when pressure drop reached 240 Pa and the skewness factor of pressure drop changed from negative to positive or vice versa. When critical conditions were correlated to pipe with 24 groove and 32 grooves, it was found that groove arrangement determine the strengthening or weakening of the turbulent flow characteristics.



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## INTRODUCTION

Much research has been conducted to find ways of reducing the baneful effects of pressure drop and of controlling fluid flows in the surface of pipe. The problem of pressure drop in fluid flow detrimentally affects many important fields of engineering, such as heat transfer, combustion, transportation and chemical production and last but not least in saving energy. In the matter of heat transfer, special attention has been given to designing small but efficient methods of heat transfer and, it appears, that grooves incised inside fluid flow pipes would be an eminently suitable method of solving this problem. Grooved pipes increase heat transfer areas, take up little space, easy and cheap to install. In the application of fluid flow which actually turbulence, the addition of grooves affects fluid boundary layer as well as viscous layer near pipe walls, which in turn determine pressure drop and viscous drag in fluid flows.

Over the years, a great deal of investigation has gone into pressure drop, fluid flow through grooves/riblets as well as their relationship to heat transfer characteristics. Aroonrat *et al*. (2013) researched heat transfer and flow characteristics of water flowing through horizontal internally grooved pipes made of stainless steel at Re equal to 4000 to 1000 and found that the thermal enhancement factor of these grooved pipes was 1.4 to 2.2. Katoh *et al*. (2000) studied the relationship between heat transfer enhancement and increasing drag due to surface roughness in turbulent channel flows and discovered that these roughness elements had a significant effect on heat transfer. Choi and Orchard (1997) looked into the characteristics of heat transfer from triangular-profiled riblet surfaces in wind tunnels, the results showed that heat transfer coefficient rose by 10% compared to the pipes without riblets.

Studies into flow behavior, vortex interaction as well as flow structure transformation and turbulence drag-reduction mechanism indicate that there is a change in the pattern of fluid flows. Baloutaki *et al*. (2013) investigated free stream turbulence over transversely grooved surface and found that the additional turbulence from these grooves was able to raise fluid particle momentum. The grooves reduced flow oscillation and prevented the formation of horseshoe vortices (Hongwei *et al*. 2005), and in addition, the grooves were also able to stop the formation of turbulence spots (Litvinenco *et al*, 2006). Research has been done into various shape of groove to improve the flow and uncover flow structure details, such as that of Sutardi and Ching (1999) work on transverse square grooves at turbulent boundary layers, Lee and Lee (2001) on semi-circular riblet surfaces, Lee and Jang (2005) on V shaped micro riblets and Shan Huang (2011) on helical grooves.

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Although much previous work has centered on grooves shape or flow structure as it passes over grooves on flat plates, very little has been done on grooved pipe. In grooved pipes, flows are unique because of the grooves symmetrical shapes and pipe curvature. Furthermore, no research has been done into reconstructing flow behavior in grooved pipes during pressure drops. Thus, this study concentrated on calculating pressure drop when the flow behavior changes and ceases to rotate. The parameters monitored were pressure drop, skewness factors of pressure drop and radial velocity. And, in order to better observe flow details, visualization was assisted by plastic threads and a dye.

## MATERIALS AND METHODS

The sketch of the apparatus for this study is shown in Figure 1.

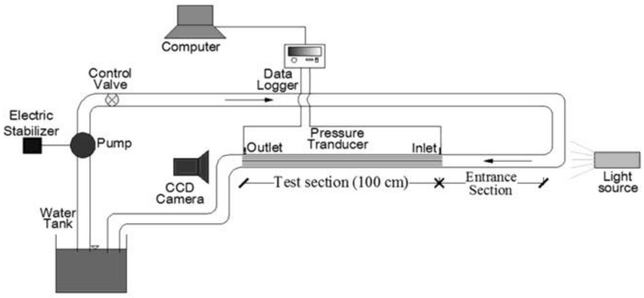


**Fig.1:** The schematic representation of the experiment apparatus set-up.

The flow was driven by a centrifugal pump, which electronically stabilized for each experiment flow rate. Control valve was installed to control volume flow rate. The Reynolds numbers (Re) investigated were 22146, 20637, 18155 and 15038 at water temperature 27±1 ºC. The pipe test section was a 2.6 cm diameter and 1m long PVC with internally etched grooves. The elbows before and after the test sections were transparent acrylic pipes for ease of lighting and visualization.

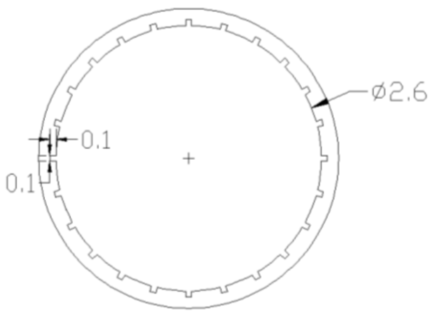


**Fig. 2:** Groove geometry (unit: cm).

The grooves were formed by using a conventional etching technique; there were 2 test pipes, one with 24 grooves and the other with 32 and a smooth (no groove) pipe as control. Figure 2 gives details of groove geometry. The entrance section lengths (*le*) were estimated using an entrance length equation for turbulent flow as shown below (Eq.1), based on pipe diameters (D) and the Re (Munson *et al*. 2005). And found to be 60 cm, since the entrance length of the experiment pipes was 70 cm, the flows in the test sections were considered to be fully developed.

$$\frac{le}{D} = 4.4(\mathrm{Re})^{1/6} \qquad (1)$$

Each pipe test section was equipped with 3mm diameter pressure taps installed at pipe test-section inlets and outlets. Pressure tubes connected the pressure taps and transducers to a set of data loggers so that nominal fluid pressure could be read from inside the pipes. In addition, with the aim of obtaining accurate pressure data, this data was recorded at a frequency of 250 Hz over 2 minutes repeated 7 times. Equation 2 below was employed to convert the pressure data for the comparisons in pressure drop between the 2 grooved pipes and the smooth (no groove) pipe into the change of pressure drop (%PD). A high-speed CCD camera at 240 fps was used to record plastic thread end movement over one minute. The video images were framed into sequential still photographs and employing image processing to obtain the velocity in a radial plane. Flow visualization data was obtained by employing a dye and the high-speed camera set at 480 fps.

$$\%PD = \left[1 - \frac{(dP/dx)_{smooth}}{(dP/dx)_{groove}}\right] x100\% \qquad (2)$$

Where a positive %PD indicated an increase in pressure drop, and a negative one indicate a decrease.

## RESULTS AND DISCUSSION

Preliminary experiments were done on the smooth pipe to establish the pressure drop and radial velocity. This data was then used as a comparison to the data from the grooved pipes. The pressure drops data in the grooved pipes at various Re number are shown in figure 3.

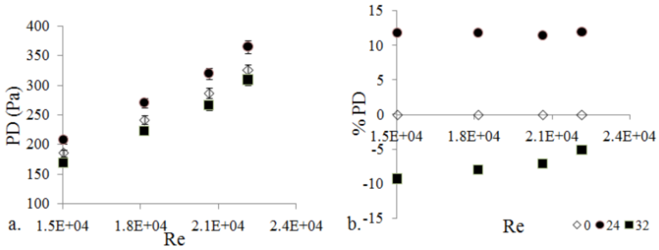


**Fig. 3:** Pressure drop data (a) Average pressure drop for various Re; (b) Changes in pressure drop of various Re.

Figure 3a shows that pressure drop rose linearly for Re in both grooved pipes. However, a more detailed examination of the pressure drop percentage indicates that changes in pressure drop for both grooved pipes uncovered an interesting phenomenon (Fig.3b). In the pipe with 24 grooves, the percentages of pressure drop change were positive, these value were relatively similar on various Re. It meant that compared to the smooth (no groove) pipe, there was an increase in pressure drop but the rise in Re did not have a significant effect on pressure drop, which was so because all the flow was turbulent and within the narrow Re range. For the 32-groove pipe this was different, the smaller the Re, the more negative the %PD, and the pressure drop lessened. This demonstrates that the more laminar, the level of molecular randomness in the fluid flows and the momentum convection are lower, which in turn induced pressure drop decreases. The grooves functioned to smooth out fluid flow by reducing region of high velocity gradients. The lower the streamwise velocity, the better the grooves functioned to reduce flow velocity fluctuations.

Figure 4 shows the pattern of the relationship between number of grooves and radial velocity as well as skewness factors of pressure drop at various Re. Figure 4a shows that in the case of the decrease in pressure drop (32 grooves), had a lower radial velocity than that for the smooth pipe. Whereas, in the case of the increase in pressure drop (24 groove), the radial velocity was higher than that for the smooth pipe. This coincides with PD in fig. 3a where the pressure drop was proportional to the radial velocity, for when there is an increase in pressure drop, there will also be a corresponding increase in radial velocity. Figure 4b lays out skewness factors of pressure drop. When the skewness factor is positive, the flows tend to have pressure drop lower than average pressure drops of smooth pipe so that over all pressure drop decreases. Whereas, where the skewness factor is negative, the flows tend to form higher than average pressure drops of smooth pipe, so that pressure drop increases. Figure 4b shows that an interesting phenomenon also appears at Re = 20637 and 18155 in the smooth pipe, where the skewness factor changes from negative for Re = 20637 becomes positive for Re = 18155. This change from positive to negative in the skewness factor of pressure drop occurred at PD ≈ 240 Pa (fig.4c).

In order to reveal a more detailed, appropriate visualization was required. Therefore, a system was put into place where the movement of plastic threads attached to inner pipe walls together with a dye introduced into the flows gave an accurate photograph of what was happening. Figures 5 to 8, the red dots indicate the initial position of the plastic threads and the blue lines show their path line movements. In the smooth pipe at Re equal to 22146 and 20637, the threads tended to move towards pipe walls. However, for Re equal to 18155 and 15038, they tended to bunch together and had a shorter movement compared to that for Re equal to 22146 and 20637. In the case of pressure drop increases (24 groove), the threads moved in long lines and tended to move towards pipe walls which proves that a high velocity gradient occurred between the centre and walls of the pipe which resulted in an increase in radial velocity. Whereas, in the case of pressure drop decrease (32 groove), the threads movement lines were short and tended to collect nearly to the centre of pipe. It proves that low velocity gradient occurred between the centre and walls of the pipe that resulted decreases in radial velocity

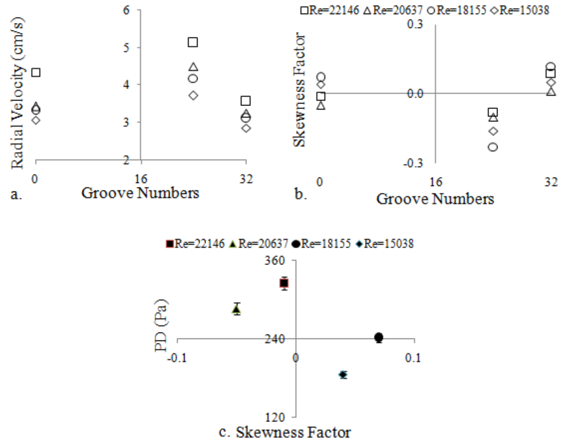


**Fig. 4:** Pressure drop, radial velocity, skewness factors of pressure drop and groove number relationships. (a) Radial velocity; (b) Skewness factors for various Re; (c) Pressure drop as a function of the skewness factor for the smooth pipe.

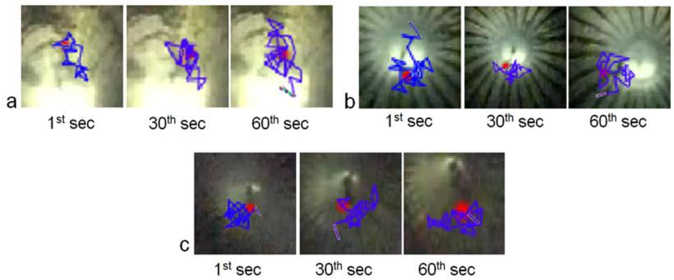


**Fig. 5:** Thread movement patterns inside the pipes at Re= 22146 (a) no groove; (b) 24 grooves; (c) 32 grooves.

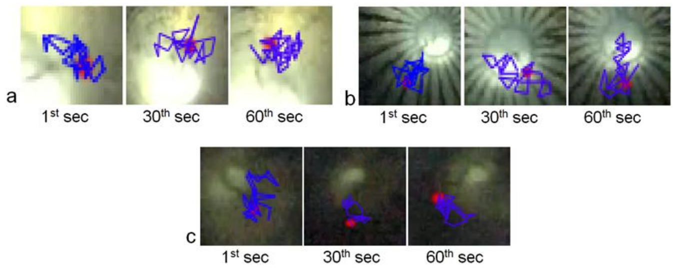


**Fig. 6:** Thread movement patterns inside the pipes at Re= 20637 (a) no groove; (b) 24 grooves; (c) 32 grooves.

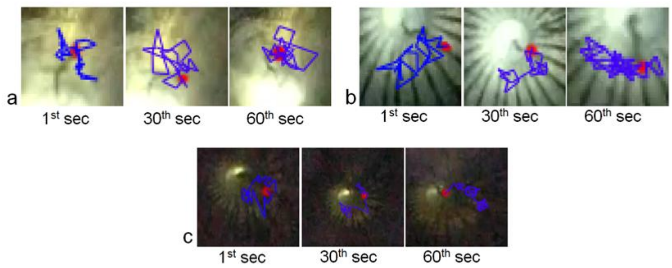


**Fig. 7:** Thread movement patterns inside the pipes at Re= 18155 (a) no groove; (b) 24 grooves; (c) 32 grooves.

**Australian Journal of Basic and Applied Sciences,** 8(9) June 2014, Pages: 187-194

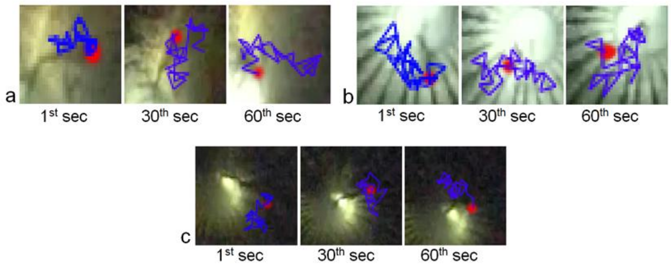


**Fig. 8:** Thread movement patterns inside the pipes at Re= 15038 (a) no groove; (b) 24 grooves; (c) 32 grooves.

For further understand the pattern of fluid flow in the smooth, the 24 grooves and the 32 groove pipes, a dye was employed to help visualize and uncover details of fluid flow behavior due to the grooves. Figure 9 to 12 show the dye patterns at the outlet sections of the pipes.

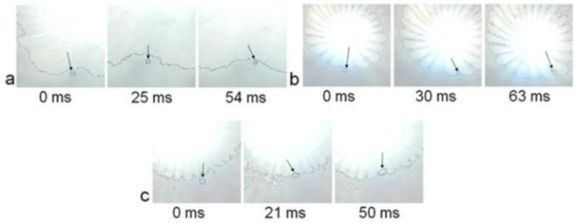


**Fig. 9:** Dye pattern at the outlet sections of the pipes at Re= 22146 (a) no grooves; (b) 24 grooves; (c) 32 grooves.

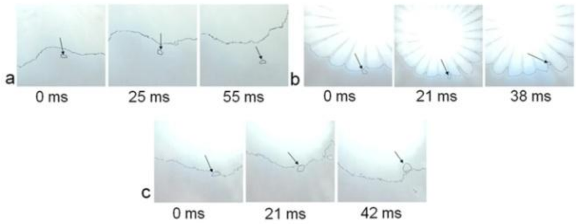


**Fig. 10:** Dye pattern at the outlet sections of the pipes at Re= 20637 (a) no grooves; (b) 24 grooves; (c) 32 grooves.

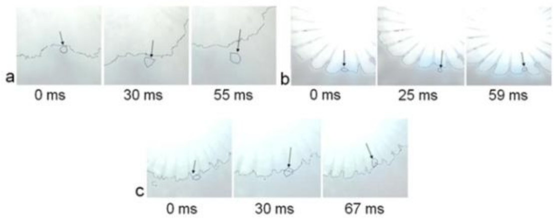


**Fig. 11:** Dye pattern at the outlet sections of the pipes at Re= 18155 (a) no grooves; (b) 24 grooves; (c) 32 grooves.

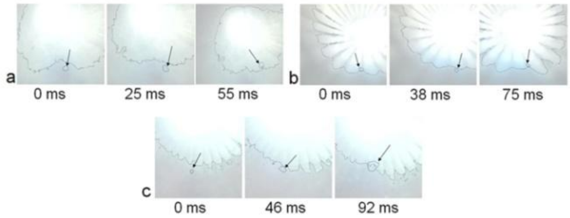


**Fig. 12:** Dye pattern at the outlet sections of the pipes at Re= 15038 (a) no grooves; (b) 24 grooves; (c) 32 grooves.

Assuming that fluid lump considered being actually vortices, the visualization was able to measure these vortex sizes for various Re. In the smooth, 24 groove and 32 groove pipes at Re equal to 22146, the diameters of the vortices formed were 3.5, 3.5 and 8.8 pixels (px) respectively. For Re equal to 20637 they were 3.9, 4.7 and 9.8 px respectively, for Re equal to 18155 they were 8.6, 4.3 and 8.3 px respectively and for Re equal to 15038 they were 7.5, 4.6 and 9.9 px respectively (fig. 9 to 12). As a reference, groove width was 4.76 px.

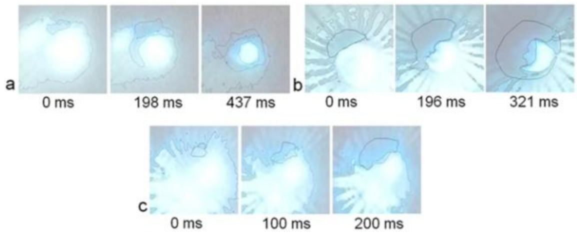


**Fig. 13:** Dye patterns at pipe inlet sections at Re= 22146 (a) no grooves; (b) 24 grooves; (c) 32 grooves.

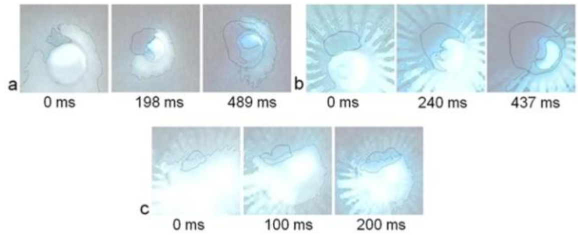


**Fig. 14:** Dye patterns at pipe inlet sections at Re= 20637 (a) no grooves; (b) 24 grooves; (c) 32 grooves.

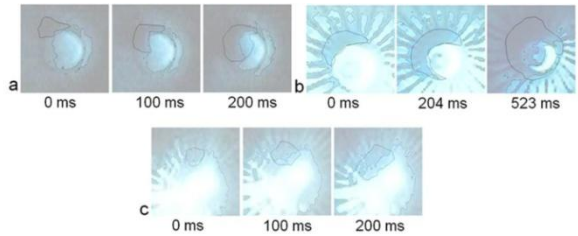


**Fig. 15:** Dye patterns at pipe inlet sections at Re= 18155 (a) no grooves; (b) 24 grooves; (c) 32 grooves.

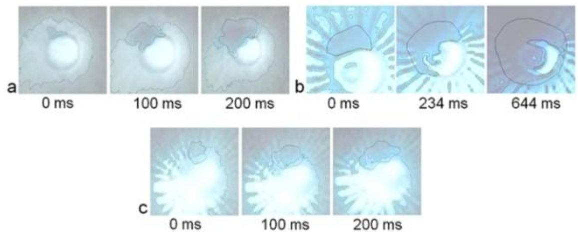


**Fig. 16:** Dye patterns at pipe inlet sections at Re= 15038 (a) no grooves; (b) 24 grooves; (c) 32 grooves.

In the smooth pipe, vortices diameters tended to increase as Re decreased (fig. 9 to 12). Any changes in vortex dimensions were indicators of change in fluid flow behavior. At Re equal to 22146 and 20637, the vortices were small in diameter and energetic which induced the fluid to whirl while it flowed to the downstream (fig. 13 and 14). However, at Re equal to 18155 and 15038, vortices formed that were larger than those at Re = 22146 and 20637. This resulted in a reduction in angular velocity and therefore also in angular momentum, as well as the energy that caused the flow to whirl, and finally the fluid diffused while flowing (fig. 15 and 16).

The formation of small vortices (smaller than grooved width) of the 24 groove pipe that whirled against the walls (fig. 13 to 16), indicated that energetic small scale vortices formed on pipe walls and swept out the large scale vortices at pipe centers. Moreover, this had a knock-on effect near pipe walls causing the fluid to whirl round. This phenomenon was confirmed by figure 4b, where the skewness factor of pressure drop was negative. Since a zero skewness means random turbulent flow, the increased pressure drop was produced by high angular velocity small scale vortices (fig. 9 to 12). Here, the vortices formed entered the groove valleys thereby increasing shear stress at pipe walls, and then increased velocity gradient, radial velocity as well as pressure drop. Things were different in the 32-groove pipe, here the vortices formed were larger than the groove width (fig. 9 to 12) and it seemed that these grooves were able to capture them and hold these vortices over themselves. Thus, shear stress did not migrate to the pipe walls and the large vortices that formed in the centre of the pipe were more dominant and were able to obliterate the small-scale ones that formed on pipe walls. Visualization results showed the dye tended to bunch together and then diffuse (fig. 13 to 16). This phenomenon prevented fluid flow whirling in the pipes, and thus reducing radial velocity as well as pressure drop. This was confirmed by figure 4b, where the skewness factor was positive.

An interesting phenomenon occurred in the smooth pipe between Re equal to 20637 and 18155, where for Re equal to 20637 the skewness factor was negative but at Re equal to 18155 the skewness factor was positive. For the presence of both negative and positive skewness factors of pressure drop indicate that there was a periodic motion in the fluid flow. The skewness factor of pressure drop is positive showed that large diameter vortices had formed and that the fluid did not whirl while flowing through the pipe. However, regarding the skewness factors of pressure drop is negative, these indicated the formation of small diameter energetic vortices which caused the fluid flow to revolve, and thus increase pressure drop.

In the smooth pipe, the critical pressure drop at the time of the skewness factor change, either to negative to positive or vice versa, was 240 Pa. At this level, the fluid state changed from whirling to non-whirling or vice versa. If this critical level from the smooth pipe is correlated to the 24-groove pipe, then when the pressure drop reached < 240 Pa, this occurred at Re equal to 15038. Here the skewness factor of pressure drop was negative, the vortex was smaller than the groove width and the fluid flow whirled from upstream to downstream. The behavior of the fluid flow in the 24 groove pipe had a Re of 15308 and a pressure drop of < 240 Pa, should have followed the flow pattern for the case of decreased pressure drop. However, the reverse occurred, as flow behavior remained that for the case increasing pressure drop and the only explanation for this phenomenon in this study, was the number of the grooves incised in the pipe. The 24 grooves were able to accelerate vortex energy at lower Re, and this resulted in increasing pressure drop (fig. 3b). Whereas, for pressure drop of > 240 Pa, started at Re equal to 18155 and at this stage the skewness factor was negative, vortices diameter were smaller than the groove width and the fluid flow whirled down the length of the pipe. This behavior was in accordance with that of the flow in the smooth pipe and even resulted in a small increase in pressure drop. This was confirmed by %PD that fluctuated a little (fig 3b.).

If the critical level of the smooth pipe is correlated to the 32-groove pipe, the pressure drop value > 240 Pa commenced at Re equal to 20637. Here the skewness factor was positive, the vortices were larger than the groove width and the fluid did not whirl as it flowed through the smooth pipe. The fluid behavior in the pipe had Re of 20637 and pressure drop of > 240 Pa, whereas, it should have followed the flow pattern for the case of increasing pressure drop. However, the behavior of the flow that forms continues to follow the behavior of the flow for the case of decreasing in pressure drop. The only explanation for this was the effect the grooves. These 32 grooves were able decelerate the vortices energy at higher Re so that they continued to achieve decreasing in pressure drop (fig.3b). Whereas, for the pressure drop of < 240 Pa, it started at Re equal to 18155, the skewness factor here was positive, the vortices were larger than groove width and the fluid did not whirl throughout its flows through this pipe. These findings corresponded to the ones for the smooth pipe fluid flows and even strengthened decrease in pressure drop, and this was demonstrated by the increasingly negative of %PD (fig. 3b).

***Conclusion:***

Measuring and visualization techniques were used to investigate the characteristics of turbulent fluid flows over internally grooved pipe. In the 24-groove pipe resulted in an increase of pressure drop, whereas in the 32-groove pipe there was a decrease of pressure drop. It was discovered that in the case of increasing pressure drop, the size of the vortices formed were smaller than the groove width so that these vortices fell into the valleys of the grooves, inducing the fluid to whirl and thus increasing radial velocity. On the contrary, in the case of the decrease in pressure drop, the dimensions of the vortices formed were larger than the groove width so that these vortices remained stationary above them and the fluid tended to diffuse and not whirl. In this investigation, it was estimated that the critical pressure level occurred when the fluid actually started to whirl and vice versa. In the smooth (no groove) pipe the critical condition appeared when the pressure drop value reached 240 Pa. Moreover, when critical conditions were correlated to pipe with 24 groove and 32 grooves, it was found that groove arrangement determine the strengthening or weakening of the turbulent flow characteristics.

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