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Experimental Study of Mixing Efficiency in Laminar Flow for Circular Pipe with Perforated Plate Mixer

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Abstract: Flow in circular pipe equipped with Fractal Perforated Plate may be another solution in enhancing flow properties in laminar flow instead of using orifice. The purpose of this study is to investigate the pressure drop in laminar flow in circular pipe with perforated plate. Three patterns of perforated plate in various porosity, β of 0.38, 0.50 and 0.70 were used for this investigation. The perforated plate patterns reacted to eight openings of discharge ball valve and resulting the finding of mass flowrate measurement, pressure drops and flow visualization. Data from the three plates suggest that there will be increment of pressure drop and reduction on mass flowrate with lower β value, thus affecting the flow conditions. This investigation also compares the turbulent mixing properties generated with and without the existence of perforated plate in the circular pipe. This study proved that perforated plate of β equals to 0.38 produced higher mixing properties in laminar flow compare to the other two other plates. This statement was strengthened by the images of flow visualization and pressure drops table gained from the experiment.

Keywords: Pressure drop, laminar flow, circular pipe, perforated plate, flow visualization.

1. Introduction

Flow in a pipe is the transportation of fluid in a closed conduit with a round cross-section [1]. Three types of flow exist in pipe flow; laminar flow, which the flow moves in layers, turbulent flow, that is a highly distorted flow of motion and transverse interchange of momentum due to inertia effects, and transitional flow, consist of random characteristics as it is the transition period from laminar to turbulent flow.

Flow through the orifice and grid plate such as a perforated plate is an example of controlling fluid flow, where the flow is separated by a sharp edge or corner [2] producing a flow mixing properties and pressure drops downstream of the pipe [3]. Fractal perforated plate is a plate with self-similarity and complex shape that will enhance the flow mixing properties and removes error due to the flow disturbances inherent to pipes connections and sudden change in direction [3]. This fractal shape is assumed to have significant effects on pressure drops and turbulent intensity owing to their properties [4].

2. Previous Work

Orifice plate or fractal perforated plate inside the circular pipe flow is mainly to be used as a device to measure the instantaneous flow rate in the pipe. A typical orifice meter is constructed by inserting a flat plate with holes between two flanges of pipe [1]. Fractal is a complex geometric pattern exhibiting self-similarity in small details of its structure viewed at any scaled repeated element. It is a derivative of classical Euclidean geometry characterized by infinite detail where the edge smoothness is absent [5]. The most popular fractal structure is the Von Koch curve which established in 1904 by Swedish mathematician, Helge Von Koch and been used in the most recent study of this area as the main reference in creating own fractal shape and objects by researchers [5,6,7,8,9].

Six papers by various researchers been reviewed by the author for obtaining the scope and generating ideas about flow characteristics. The author noticed that the papers sequenced possessing trending continuity and improves based on previous researches. The trend started by A. Staicu, et al, investigated the turbulence flow created by fractal objects inside recirculating wind tunnels where it varies at fractal objects orientations, dimensions and the distance separation in order to achieve the flow homogeneity, turbulence intensity and the scaling regions [8].

D. Hurst and J.C. Vassilicos studied the development in determining the same gains as before but added more response to

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flow pressure drops [10]. Fractal grids are used with 3 types of grids that are cross grids, I grid and square grid in 2 types of wind tunnels; recirculating wind tunnels and open-circuit wind tunnels. The varied parameters are blockage ratio, mesh size, thickness, fractal dimension and the number of fractal iteration. By taking orifice as subjects, research have been done to it by modify in into fractal shape orifice and placing it inside small wind tunnels and the data obtained were compared to the circular orifices. A. Abou El-Ezm Aly, et al evaluated the pressure drops and its velocity ranged in this investigation [6].

Interacts with preceding studies, S. M. Muztaba Salim, F.C. G. Nicolleau, and M. Borkowski try to get knowing the effects of fractal shape orifice on the flow mixing and are then carry out a study by pairing the fractal shaped orifice with a smooth orifice and varying them by flow rate area and fractal iterations number [9]. All four studies conducted inside wind tunnels using hot-wire anemometry to measure flow velocity and pressure tapping that connected to several devices to know flow pressure.

Since the flow analysis is yet to be done inside a pipe, B. Manshoor, F.C.G. A. Nicolleau, and S. B. M. Beck used water as working fluid inside a pipe [7]. The pipe equipped with a fitting to create a disturbance to the flow and decay the disturbance effect in the fractal flow conditioner is used with an orifice plate flow meter. The purpose of the flow conditioner is to shorten the pipe length in developing a fully developed flow. By varying the fractal pattern porosity and the disturbance types, this study gives a date of discharge and pressure loss coefficient and presenting the performance of the flow conditioner.

Lastly, a study of flow investigation by using baffles is appointed by Mushtak T. Al- Atabi et al [5]. Baffles ratio of height and pipe diameter been varied as well as Reynolds number in the attainment of the flow pressure drop, flow structures and the optimized number of baffles should be used in the pipe. The measurement types of device are the same as previous research explained but instead of CFD modelling, the used of flow visualization is chosen. Flow visualization is to visualize the mixing effect inside the flow which indicates the flow shift to the turbulent flow characteristics from a laminar flow characteristic.

3. Methodology

3.1 Experimental Test Rig

The experiment is carried out to investigate the pressure drop of laminar flow inside a circular pipe with a fractal perforated plate. The experiment uses a circular pipe of 2-inch diameter with water as working fluid which is supplied from the storage water tank. Elbow is introduced into the distance to create a gravity effect to the flow from the tank. The overall length of the system is 202.15 inch (5 meters) with 3 divided sections of dissimilar functions. The first 30" of the pipe is called developing flow area, to eliminate the entrance region effects to the flow thus creating a fully developed flow. Ball valve used to control the flow rate into the test section. Middle 85.15" length is the test section, consist of 42" length of clear pipe before the tested fractal perforated plate, 1.15" is the length of the fractal plate holder and another 42" length of clear pipe after the fractal plate. Here the pipe installed with a flange to hold the fractal perforated plate and 2 pressure tappings, upstream and downstream the plate. The 42" length of pipe after the fractal plate is the main test section where shows a process of flow visualization which involves dye injection, light source and camera.

After went through the test section, the flow will be introduced to the second ball valves with several specified openings which control the pipe flows and affecting the flow pressure difference and visualization. A final section is the flow settlement section of 87" length. The test rig diagram is shown in Fig. 1.

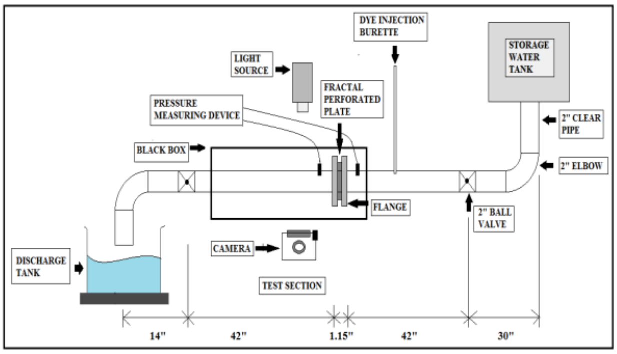

Fig 1 - Schematic Diagram of Water Test Rig

3.2 Experimental Procedures.

The 2" ball valve upstream and downstream the pipe needs to be in the closed position before the experiment is conducted. Dye injection syringe is to be connected tightly with no leakage. The fractal perforated plate is placed between two flanges installed at the circular pipe and the test section is then be enclosed by a black box. The ultraviolet light is to be sure to penetrate the slid on the black box and the camera is standby near the test section. The pressure tappings are connected to the pressure measurement meter tube. The discharge tank with a marked area is placed at the end of the pipe to get the flowrate data. These tests are conducted using three types of fractal perforated plate with various diameter ratios, β of 0.38, 0.50 and 0.70 as in Fig. 2 with 8 openings position.

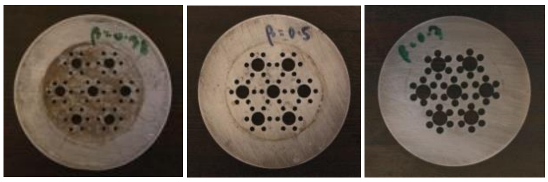

Fig 2 - Fractal Perforated Plate with β=0.38, 0.50, 0.70

After the water has fully loaded inside the storage tank, the upstream ball valve opened to let through the flow into the test section and fills the pipe. It has to be sure that no air bubble traps in the pipe and manometer tube. After all, have been prepared, the experiment can proceed by opening the downstream ball valves with the first openings. Fluorescent dye then injected to the flow through the syringe provided. Inside test section flow with a fluorescent dye is flowing through the fractal perforated plate. This will create distortion to the flow and the camera will capture the flow structure image after it went through the plate.

Pressure tapping reading is recorded using the tube manometer by measuring the height difference of tapping before and after the flow pass the test section. To gain the flow rate measurement, observe the marked discharge tank. As the water inside the discharge tank reaches the first mark on the discharge tank, start the stopwatch and wait until the water reaches the second mark to stop the count. The downstream ball valve is then shut back and the discharge tank is emptied for the next task.

Same procedure repeated for the second until eight openings of the downstream ball valve for each fractal perforated plate type. After gaining and recorded all the data into a table provided, discharge all the water inside both the pipe and the storage tank. Lastly, close both ball valves and disassemble the test rig. There are three data gains needed to be recorded in this experiments which mass flowrate analysis, pressure drop analysis and flow visualization analysis.

4. Results and Discussion

4.1 Mass Flow Rate

Mass flow rate value is being used in calculating the flow velocity and Reynolds number and can easily be classified as a laminar or turbulent state. The period of time data while discharge flow is filling a certain amount inside the discharge tank is being recorded. The data is then used to calculate the mass flow rate by dividing the water volume inside the discharge tank which is (0.48m x 0.30m x 0.05m) with the time recorded earlier. Equation 1 is used for mass flow rate calculation.

$$q_m = \frac{\mathcal{V}}{t}\ (m^3/s) \qquad (1)$$

Where q_m = Mass Flowrate, $\mathcal{V}$ = Volume of water (0.48m x 0.30m x 0.05m) and t = Time (As recorded by stopwatch)

Fractal Perforated Plate Type 1 having the smallest diameter ratio, β which is 0.3. As the β is the smallest, it should take the longest time to fill up a certain amount inside the discharge tank. At the 1st opening of the downstream valve which only exposed a little space for the flow to go through the time, it takes 127.57 seconds. The time keeps on shortens at each opening as larger the space exposed. At the 2nd opening, it slumps to 33.56 seconds and keeps decreasing until the 8th opening it gives the lowest time of 6.23 seconds. As the opening getting larger, the flow will speed up and shortening the filling time. The mass flow rate calculated by the gains of volume and time and then converted to kg/s units. The ranged of mass flow rate from the first opening to eight openings are 0.0564 kg/s to 1.1557 kg/s.

Fractal Perforated Plate Type 2 having a moderate ratio of diameter with β of 0.5 present the data range time starts with 94.73 seconds at the 1st opening. It clearly showed that as the β value increases, the filling time shortens. The time keeps on decrease rapidly to 20.35 seconds for the 2nd openings and the time range drops to the lowest of 5.18 seconds at as the opening increases. Ranged of the mass flow rate for the first opening to the eight opening are between 7.60E-5 to 1.29E-3 mm3/s which then converted to kg/s unit with values of 0.0760 to 1.2950 kg/s. Data gains are slightly higher compared to the Type 1 Fractal Perforated Plate data.

Highest diameter ratio examines here are the Fractal Perforated Plate Type 3 with a β value of 0.7. As the higher β value used, it affects the filling time to be shorter than the other two types of fractal plate. The time starts with 32.35 seconds for the 1st opening which is more than half lower than type 1 and 2. Ranged of time continues with 20.86 seconds and reach the bottom value of 4.80 seconds at the 8th openings. The mass flow rate for Fractal Perforated Plate Type 3 also shows higher value at each opening. The diameter ratio positively affecting this increment of mass flow rate over time. The first opening with a value of 0.2226 kg/s and followed by 0.3452 kg/s, 0.5158 kg/s and keeps on increasing to the top at 1.500 kg/s for the eight openings.

4.2 Pressure Drop Analysis

Pressure drop of flow inside a pipe is influenced mainly by the appearance of disturbances the flow encounter as it flows through the pipe. The data of pressure drops, velocity and Reynolds number are calculated using equation 2, 3 and 4 accordingly.

$$\Delta p = \rho g h \qquad (2)$$

That is Δp = Pressure drop in pipe, ρ = 1000 kg/ m^3, g= 9.81 N/kg and h = Collected data of height difference of tappings before and after test section.

$$V = \frac{q_m}{\rho A} \qquad (3)$$

That is V = Flow velocity, $A = \frac{\pi(50.8\times10^{-3})^2}{4} = 2.027\times10^{-3}\ m$ and q_m = Mass Flowrate (kg/s)

$$Re = \frac{\rho V D}{\mu} \qquad (4)$$

That is Re = Reynolds Number, D = Pipe Diameter (50.8 x 10^{-3} m) and $\mu = 1.002\times10^{-3}\ N.s/m^2$

Referring to graph in Fig. 3, it clearly expressed that all three type of perforated plate creates an escalation patterns data of pressure drop against Reynolds number with varies value of diameter ratio. For Type 1 perforated plate with smallest diameter ratio of 0.38 shows the most declivous line starting from a laminar value of Reynolds number which is below 2000 for the 1st openings with only less than 20 N/m^2 of pressure drop and increasing gradually to the highest value of above 30000 at the 8th opening with value of pressure drop reaching 10000 N/m^2.

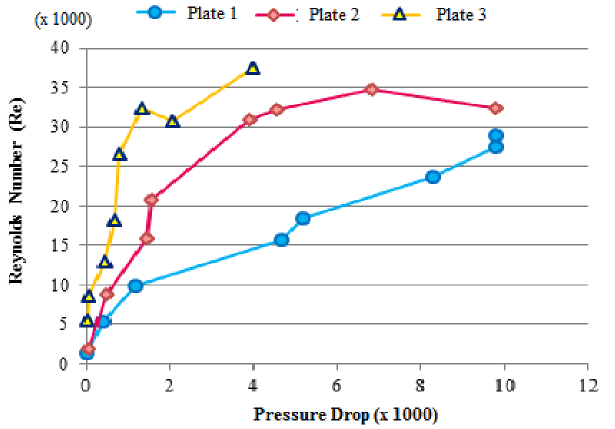

Fig. 3 - Pressure Drops against Reynolds Number Perforated Plates

For Type 2 perforated plate with 0.5 value of diameter ratio, the graph shows a medium degree of data which also starts from below 2000 of Reynolds number with pressure drop value below 50 N/m2 and it keeps increasing proportionally with Reynolds number value peaks at 35000 with above 10000 N/m2 of pressure drop. The steepest graph line showed by biggest diameter ratio of 0.7 is Type 3 of Fractal Perforated Plate where with a value of pressure drop only at 20 N/m2, the Reynolds number produces already reaches about 5000 indicates it is at the turbulent state of flow. The graph mounts up erratically to above 35000 value of Reynolds number with only 4000 N/m2 of pressure drops.

It can be explained that lower Reynolds number can be created with a smaller diameter ratio of perforated plate, however, it will result in an increment of pressure drops value. This situation can be controlled by decreasing the flowing area to slow down the flow velocity thus lower the pressure drops. If the Fractal Perforated Plate diameter ratio is larger, the pressure drops will be lower but the flow will not be in laminar flow state as desired.

4.3 Flow Visualization Analysis

Main reason of this analysis is to examine the mixing condition of flow inside a circular pipe with fractal perforated plate. The flow visualization images produce by the combination of fluorescent dye injection, ultra-violet (UV) light, black box and a digital camera. The dark surrounding of the test section inside the black box needs an existence of UV light to enhance the color of fluorescent dye injected into the flow which will allow the digital camera to captures the flow acted. Images were captured in sequence over 3 second time gaps.

Fig. 4 shows the flow condition through the Type 1 perforated plate after each opening which has been injected with dyes. For the 1st opening, the Reynolds number value is 1410.36 which mean a laminar flow state. Based on the 1st image, the fluorescent dye solution slowly mixed with the flowing water over time range of t_5 to t_9. At t_{10} both fluids mixed well and flow out from the pipe. With only a small opening the discharge valve, mixing process occurs slowly but it still achieved fine mixing efficiency. Reynolds number for the 2nd and 3rd discharge valve openings is 5361.13 and 9918.38 respectively, which presents turbulent flow has proven the statement of fractal plate create a turbulent flow and satisfy the higher mixing efficiency which are clearly visualizes by the mixing of the fluorescent dye solution and flowing water thoroughly.

The mixing process was faster than at the 1st opening as the flowing space increases. For the 8th opening produces Reynolds number value of 28879.51 with wider openings and higher flow velocity thus resulting clearly a turbulent flow where bubbles appear along the pipe. The fluorescent dye solution can hardly be seen in this image and this can be said that both of the fluid have mixed completely and become one. It has mixed straightaway at t_3 and t_4 after the dye being injected into the flow.

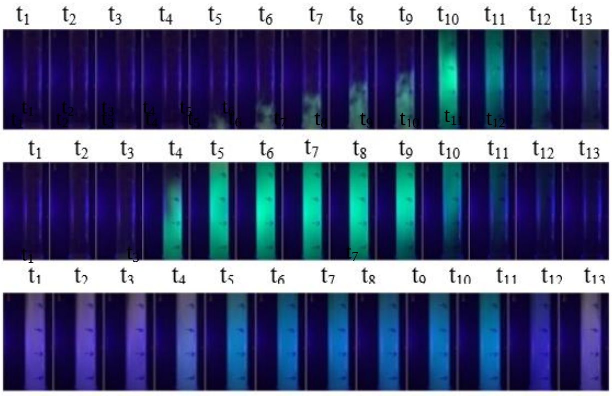

Fig 4 - Flow visualization for perforated plate Type 1

For Fractal Perforated Plate Type 2 of 0.5 diameter ratio, the flow is visualized in Fig. 5. As the diameter ratio increase, the flowing area also increases which expected to give resistance to the flow and creates mixing of the flow. With the 1st opening, it gives 1899.29 of Reynolds number which indicates a laminar flow state and shows less efficient mixing where the fluorescent dye is mixed unevenly throughout the flow. With small openings it is still producing a slower movement of mixing and flowing inside the pipe between times of t_3 to t_8. Started with the 2nd opening and further, the flow types showed turbulent flow state and proven by the Reynolds number value of 8841.25 until 32359.60 for the 8th openings. The flow shows fully mixed fluids of dyes and flowing water with instantly occurrence at t_3 and t_4 of mixing process.

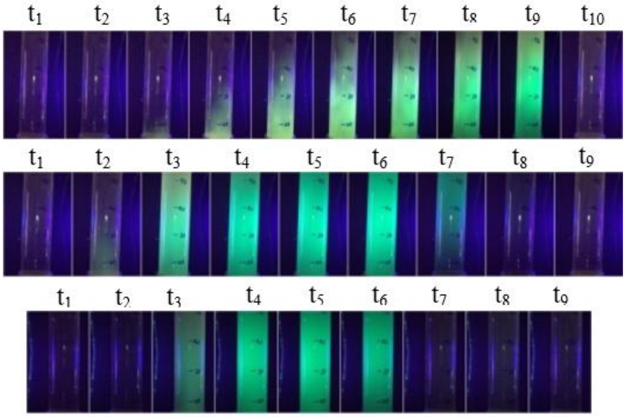

Fig. 5 - Flow visualization for perforated plate Type 2

With a diameter ratio of 0.7, Fractal Perforated Plate Type 3 was widest circular pattern cuts on it which gives larger flowing area. This plate is selected to know does the fractal plate porosity give an impact to the flow conditions. Detail flow visualization is shown in Figure 6. Reynolds number for the 1st opening is 5561.65 which is turbulent flow. Compared to previous two plates, this plate did not produce a laminar flow even at the first opening of the discharge valve. Here it can be said that the diameter ratio gives an impact to the flow conditions. The flow is moving slowly from time range of t_2 to t_8 since the small entrance created by the discharge valve opening. For the 2nd openings until the 8th openings, Reynolds number recorded is 8625.09 to 37483.20 which indicates a turbulent flow state. As the opening grows wider, the mixing efficiency also increases and mixed thoroughly at shortest ranged of time.

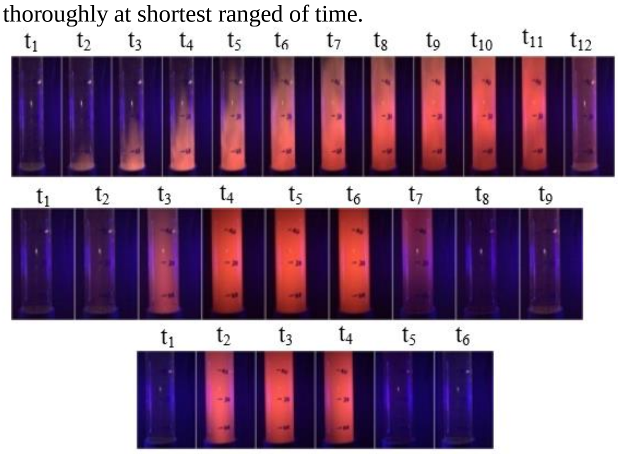

Fig. 6 - Flow visualization for perforated plate Type 3

Fig. 7 illustrated the contrast of a flow without the perforated plate. It clearly shows the fluorescent dye solution did not mixed completely with the flowing water. By the 1st openings the fluorescent dye solution hardly seen from time rage of t_1 to t_{15} as the flow is to slow and the solution have scatterd but not mixed. As the openings is expanded, the flow velocity increases and here it have lit up the fluorescent dye solution flow through the pipe without a total mixed up with the flowing water. There is clear gaps of water appear in the pipe and it has certify the needs of Fractal Perforated Plate existence in a pipe flow.

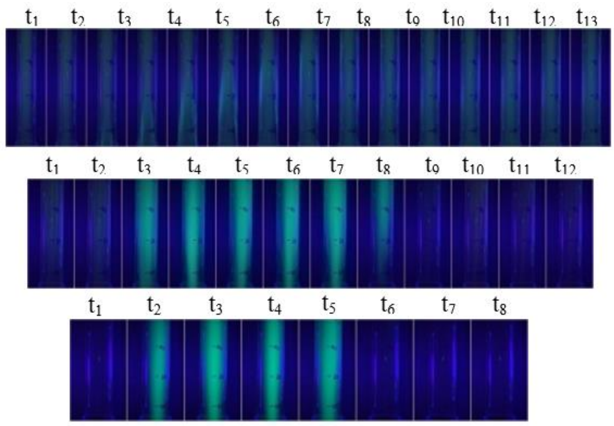

Fig. 7 - Flow visualization for without perforated plate

5. Conclusion

Flow conditions and properties through a circular pipe do effects with the existence of perforated plate. The mass flowrates and pressure drops analysis are interconnecting to each other. In findings of pressure drop analysis, mass flow rates need to be determined first and the data then is transferred to the pressure drop analysis. Time of flow filling a specified amount of discharge tank discovered for each plate is shortens with each opening and results in an increment of mass flow rates. However, the increment did not occur at the same value for perforated plate Type 1, 2 and 3. There are expanding range of time of plate type starting with the biggest range for plate type 1, followed by a medium range of time for type 2 and the smallest range are type 3 plate.

Based on all of the graph and data of perforated plate Type 1, 2 and 3, all three types of plate creates turbulent state flow with various values of pressure drop, mass flow rate and velocity rates. Type 1 and 2 plate produces a laminar flow state even it is only at the first opening but not for type 3 plate. A smaller ratio of plate diameter and the downstream valve opening area resulting in lower Reynolds number value and vice versa. With the result established, can be said that to gain laminar flow state and creates a transition to turbulent flow state, the plate diameter should be much smaller but the fallbacks are the pressure drops will be increased. For the flow visualization analysis, the diameter ratio of the plate and the flowing area interacts in enhancing the mixing properties of the fluid. The smaller the diameter ratio with the least flowing area creating a high efficiency of flow mixing even in a laminar state of flow. When the flowing area widens, it increases the flow velocity thus exciting the flow and turns it into turbulent flow thus also increase the flow mixing efficiency.

Even though turbulent flow increases the mixing of flow, it will result in higher pressure drops. This is why laminar flow is suggested in these experiments. By taking into account the needs of low-pressure drops and high flow mixing, the Fractal Perforated Plate need to be designed with a smaller diameter ratio of the fractal which will interact better with each flowing area creates by a discharge valve openings in gaining an optimum flow condition.

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