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Design and Analysis of a Water Pipe Leakage Sensor

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ABSTRACT

Water pipeline leakage is a common problem in almost every country in the world which has become a shared concern today. While some regions do not even have the access to clean and treated water, others have seen millions of litres of water wasted every day due to leakages which probably could have been sufficient to serve the needy. In most cases, the detrimental effects associated with the occurrence of leaks may present serious problems and therefore, leaks must be quickly detected, located and repaired. Recent advances in sensor technology have resulted in a wide application of sensor networks for the purpose of leakage management. Currently, researchers have gone as far as putting the sensors inside the pipeline itself to identify, locate and estimate the leak size. In the current study, CFD simulations were used to find the drag coefficient associated with the designs prepared which is an important parameter in this study. The work has been validated with the previous work. The main outcome from the study was the drag coefficient produced from the proposed model is significantly higher than the reference design. For the water pipe case, this a favourable outcome.

1. Introduction

The occurrence of leaks may be the consequence of several reasons including damage and manufacturing flaws, bad workmanship, sudden changes of pressure, cracking, internal and external corrosion, and defects in pipes or lack of maintenance [1]. Usually, the leakage from external pipes is easily detected and through visual inspection and the use of some bulky devices. However, underground pipes pose a different challenge in order to supervise the leaks and this is where tiny in-pipe sensor should come handy. Underground drainage due to leaks may result in problems such

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as damage to building and structure, deterioration of building materials, soil erosion and contaminants infiltrating from the leaky pipe [2].

The water that has been produced and lost before it reaches the customer is termed as Non-Revenue Water (NRW). In Malaysia specifically, more than 4.27 billion liters of treated water are leaking out of the country's ageing pipe system every day as of 2014. It is quite astonishing to note that this figure alone was enough to fill more than 1,700 Olympic-sized swimming pools or supply Perlis' water demand for 53 days [3]. The worst part is that it will cost a whopping RM 500000 to replace just 1 km of 44000 km-long asbestos-cement pipes nationwide [4]. Thus, proper management of pipeline leakage is deemed to be the most realistic option that is applicable in the near future although old pipe replacement is a must.

Water pipeline leakage can be apparent when the water enter penetrates the layer above the damaged location and emerge on the ground surface. It can also be hidden and only become noticeable when the water swells through the sewerage system or the pipeline networks. Some of the most frequently found factors of pipeline damages are the application of improper pipes, hard contact on the pipes, ground deformations, corrosion or erosion of the inner wall of the pipes and ageing polymer materials [5].

The works on water pipeline leakage have been explored by many since the turn of the century. A handful of techniques to detect leaks in water pipeline are practiced in the industry such as water audits by metering, listening devices, leak noise correlators, pressure transients, tracer gas technique, thermography and ground-penetrating radar. For example, Roy [6] has patented the usage of leak noise correlators which are portable microprocessor-based devices that use the cross-correlation method to pinpoint leaks automatically. Meanwhile Hunaidi [7] performed leakage sensing works by using sensitive mechanisms or materials such as piezoelectric elements to sense leak-induced sound or vibration. Aside from the methods mentioned above, non-acoustic approaches such as tracer gas technique (TGT), infrared thermography and ground-penetrating radar (GPR) have also been touted as potential leak detection methods according [8]. Another popular non-acoustic method reviewed is ground-penetrating radar (GPR) which is suitable for buried underground pipes [9]. Lately, inspection robots have become the area of interest for in-pipe leakage inspection which is compatible for underground pipelines. Liu [10] reviewed the usage of miniature robots for video and laser check-up by Inspector Systems. Another breakthrough in robotic system pipe inspection has been developed by a team of researchers called PipeGuard [11] at Massachusetts Institute of Technology (MIT). The robot looks like an enlarged badminton shuttlecock made up of rubbery materials and soft membrane. The application is simple enough that it can be inserted into the water system through any fire hydrant and then retrieved using a net at another hydrant. Jamoussi [12] have presented in his paper on the fundamental requirements of such systems include the ability to traverse the entire pipe in a reasonable time without getting stuck; ability to inspect the pipe with acceptable accuracy and resolution, and ability to transmit the inspection data to the outside for reporting or save the data locally for later retrieval. According to Chatzigeorgiou [13], the ideal specifications of a sensor module should take into account the characteristics such as autonomy, leak sensing sensitivity, working conditions, communication and localization. Bond [14] presented a tethered system that pinpoints the location and estimates the magnitude of the leak in large diameter water transmission mains of different construction types. Carried by the flow of water, the system can travel through the pipe and in case of a leak; the leak position is marked on the surface by an operator, who is following the device.

In the current study, a new shape of leakage sensor inserted into the pipeline is proposed. CFD simulations are used to check the performance of the design. The main parameter that indicates its performance is the drag parameter. Significance of this study is can be noticed on the environment well-being. This is reflected by stopping water from permeating into the ground by detecting the leaks in the pipe earlier so that preventive actions can be done. As a result, the risk of soil erosion and can be diminished as the accumulation of water in the ground from pipes that have burst can be associated with the movement of property and the property grounds. Landslide may seem a much larger scale of something that could happen but the principle is much the same.

Finally, water companies can greatly benefit from the latest advancement of technology in dealing with water pipeline leak detection. The introduction of a new method in this field would provide a better and much improved alternative to the existing methods that have been used for quite some time. It may cut down the cost of operation for leaks detection which means that the budget can be better spent for other purposes. In the long term, the companies may increase the net revenue just by simply reducing the losses and improving the quality and effectiveness of the water distribution system.

2. Methodology

2.1 Design of the Leakage Sensor

The design criteria for the leakage sensor is as shown in Table 1. The most important thing to consider in the design is the size of the mobility module itself which will host all other instrumentation and equipment inside its body. At the same time, it also must be small enough so that it can satisfy the space limitations within a very strict pipe environment. In this case, the diameter of the pipe used is 100 mm which will be the benchmark of the limitations of the module. This means that the module's diameter or width should never exceed the pipe's diameter. The pipe geometry must also be analyzed in determining the size of the module to ensure a seamless travel inside the pipe.

Table 1
Design Criteria

Size	The mobility module must be small enough to be fitted in pipes with a diameter of 100 mm.
Mobility	The module must be able to travel seamlessly through complicated pipeline configurations ranging from straight pipes to bended sections.
Free Floating	The module has to float passively inside the pipe with a speed V_m, smaller or equal to the speed of the flowing water V_w.
Speed Control	The mobility module should induce enough drag to control and reduce its speed at suspicious locations for finer and more accurate leak detection.
Stability	The module has to retain a steady and stable movement inside the pipe even after hitting the walls while floating.

The following Figure 1, Figure 2 and Figure 3 show the CAD designs that have been prepared according to the above criteria together with their respective dimensions.

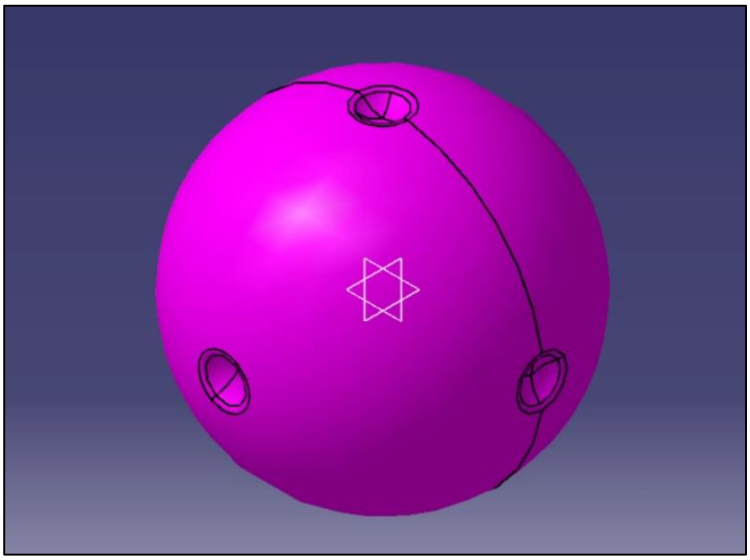


Fig. 1. Design 1 with a diameter of 50 mm figure quality

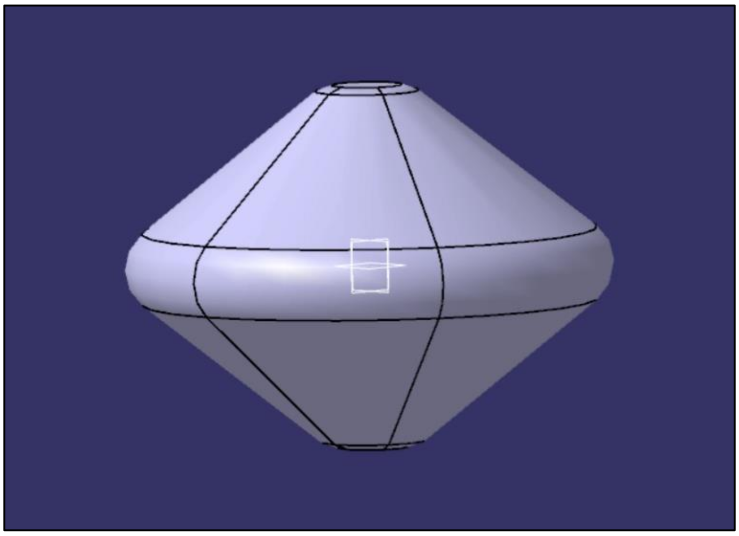


Fig. 2. Design 2 with L=80 mm and H=50 mm

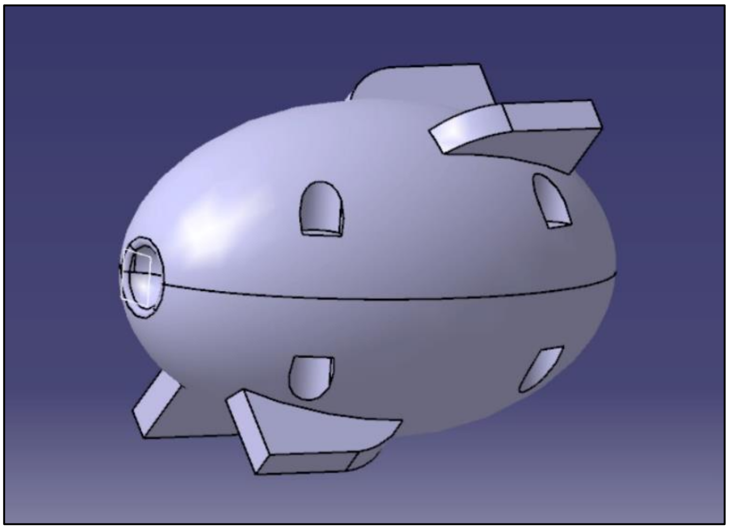


Fig. 3. Design 3 with L=80 mm and H=50 mm

2.2 CFD Setup

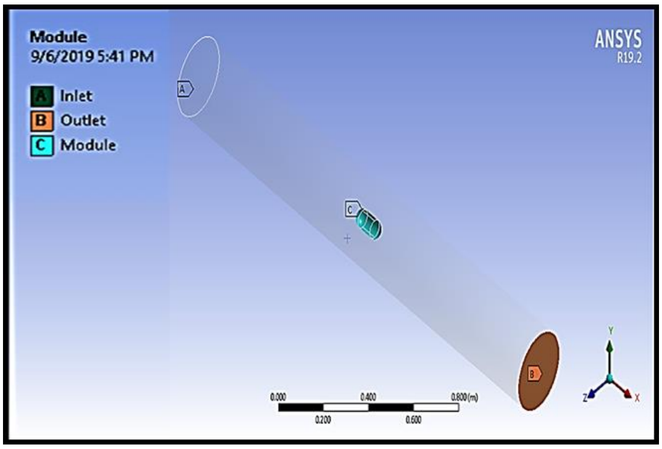
Computational fluid dynamic simulations have been performed with the ANSYS 19.2. The software uses the RANS equation to solve the fluid dynamics equations. The instantaneous continuity equation, momentum equation and energy equation for a compressible fluid can be written as:

$$\frac{\delta\rho}{\delta t} + \frac{\delta}{\delta x_j}\left[\rho u_j\right] = 0 \tag{1}$$

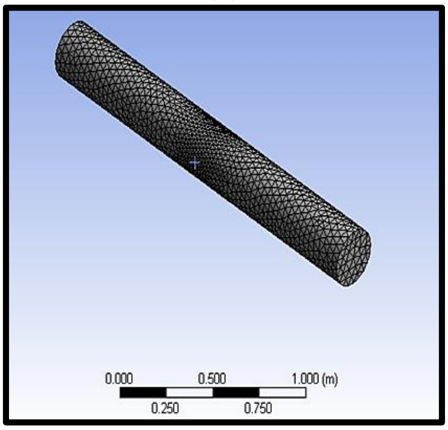
$$\frac{\delta}{\delta t}(\rho u_i) + \frac{\delta}{\delta x_j}\left[\rho u_i u_j + p\delta_{ij} - \tau_{ji}\right] = 0, \quad i = 1,2,3 \tag{2}$$

$$\frac{\delta}{\delta t}(\rho e_0) + \frac{\delta}{\delta x_j}\left[\rho u_j e_0 + u_j p + q_j - u_i\tau_{ij}\right] = 0 \tag{3}$$

CFD package (FLUENT) to study the flow pattern around the body inside a pipe of 100 mm in diameter. The setup of the current CFD simulation is following the setup by Hamad *et al.,* [15]. Steady state 3D turbulent flow simulations have been used to study the flow field, the pressure distribution around the body, velocity vectors and the calculation of drag coefficient. The standard k-ε model is used for turbulence and the inlet velocity and pressure outlet boundary conditions are applied. Figure 4 shows the leakage sensor located at the centre of the pipe and the mesh of the whole fluidic section which consists of a pipe of length 2 m and 100 mm in diameter.



(a)



(b)

Fig. 4. (a) The leakage sensor located at the centre of the pipe and (b) the mesh inside the pipe

The velocity of flowing water is 2 m/s for a typical water distribution network. The body of the mobility module should flow with a speed which is very close to the water speed in normal situations. For the validation and actual simulations, the line pressure was set constant to 200 kPa in which it was applied to the boundary conditions of the outlet section. The pipe wall was modelled as stationary while the module's body was applied with 'no-slip' boundary conditions. The standard k-ε model was selected due to its good convergence rate.

For validation purposes, a CFD simulation was first done on the similar previous work by Chatzigeorgiou [13]. From the validation process, the drag coefficient experienced by the original design was computed. From the mesh characteristics in Table 2, the validation results yielded a drag coefficient of 0.21 while the original results stood at 0.1984 which means that there is an error of 5.85%. Since the error is below 15%, the results are considered as valid and verified.

Table 2
Mesh characteristics

Characteristic	Original	Validation
Number of Elements	1.018.974	1.062.454
Number of Nodes	186.118	197.188
Maximum Skewness Factor	0.81	0.79
Average Skewness Factor	0.22	0.23
Length of Pipe	2 m	2 m
Diameter of Pipe	100 mm	100 mm
Drag Coefficient	0.1984	0.21

3. Results

3.1 Drag Coefficient

For every CFD simulations done, the drag coefficient was computed and compared as displayed in Table 3. From the results obtained, Design 1 has the lowest drag coefficient which is below the reference design. This is expected based on the spherical design that permits a smooth flow over the surface. The presence of dimples has always been known to reduce drag aerodynamically which is why golf balls are designed rightly so. The data from the simulation has now proven that dimples may reduce drag underwater too.

Table 3
The drag coefficient calculated for every design

Design	Drag coefficient, C_D
Reference (Validation)	0.2100
1	0.1505
2	0.3392
3	0.5730

Design 2 has a higher drag coefficient than the reference design which may be related to its shape that resembles a spinning top. The motion inside a water pipes is predicted to be quite tumultuous and this might justify the higher drag produced. It has two points of contact at the top and bottom as it flows through the water. Both points may be the location where the drag is induced as otherwise the body also has a smooth design.

The highest drag coefficient is recorded from the simulation of Design 3 which has the basic shape of rugby-like ovoid. Both the front and rear tip have been dimpled to reduce drag as it meets the water. However, the presence of dual 'fins' at opposing sides of the body might be the factor that elevates drag. The presence of extra surface area provides an interference to the flow which slows down the motion of the module. It is a desirable feature as the module can stop at suspicious locations to have more time to detect the leakage for better accuracy.

3.2 Velocity and Pressure Contours

Figure 5 shows the velocity vectors that surround the body of the Design 1. The body is moving from right to left where the water comes from the inlet. Since it is a spherical body, any point on the surface can be the point of contact with water. Nonetheless, one of the dimples is selected to be the contact point where the velocity is found to be lower than the sides after has flowed through. The maximum velocity from the simulation is 3.306 m/s. It can be observed that the highest pressure occurs at the point of contact on one of the dimples. In this case, the maximum pressure is experienced at the location where the velocity is the highest. The pressure descends at sides of the body where the relative velocity is found to be the highest. The presence of dimples decreases the pressure on the smooth surface of the body.

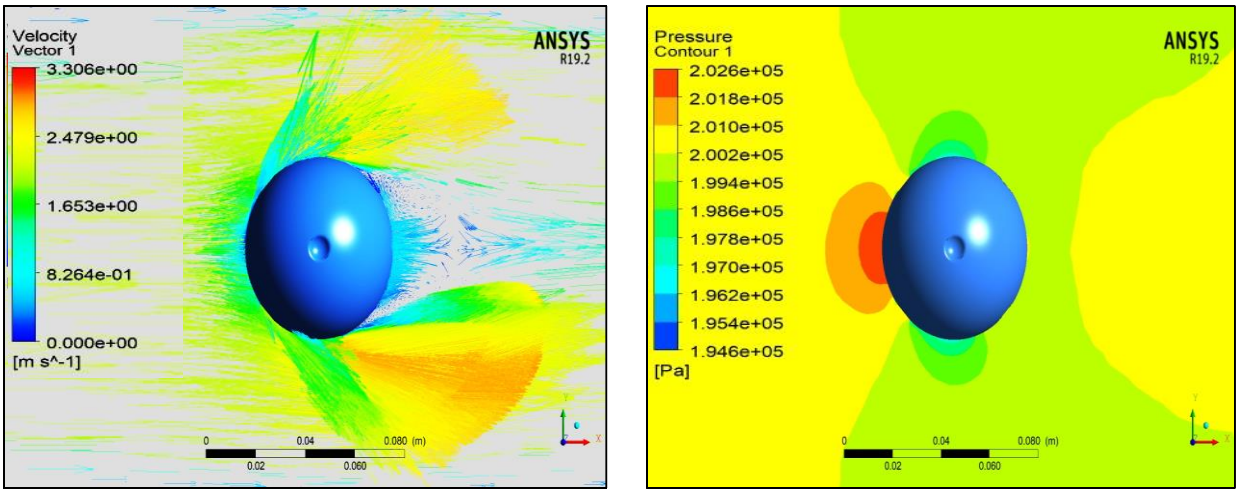


Fig. 5. The velocity vector and pressure distribution around the Design 1

Figure 6 shows the velocity vectors that surround the body of the Design 2. The body is moving from right to left where the water comes from the inlet. It can be observed that the velocity vectors are distributed evenly around the whole body. This may result in a topsy-turvy movement inside real water pipes as the shape of the design itself is purposely designed to cater such motion. The maximum velocity from the simulation is 2.629 m/s. It also can be observed that the highest pressure occurs at the point of contact at the front tip of the body. Actually, the design can be viewed as almost a cylinder which explains why the pressure profile does not change much around the whole body. The pressure decreases just before the point of contact as well as at the rear end while it drops further a bit at the sides.

Figure 7 shows the velocity vectors that surround the body of the Design 3. The body is moving from right to left where the water comes from the inlet. The location of dimple at both ends play an important role to reduce the velocity as it hits the water. The dual fins also act as 'brakes' for the module to decelerate for longer time of leakage detection. The maximum velocity from the simulation is 2.947 m/s after which water has passed through. It can also be observed that the highest pressure occurs at the point of contact at the front tip where the dimple lies. The surface of the dual fins that face the flowing water is also expected to be the spot where pressure is high due to the turbulence created. The pressure descends a bit at both sides of the body towards the rear end where relative velocity is found to be the highest.

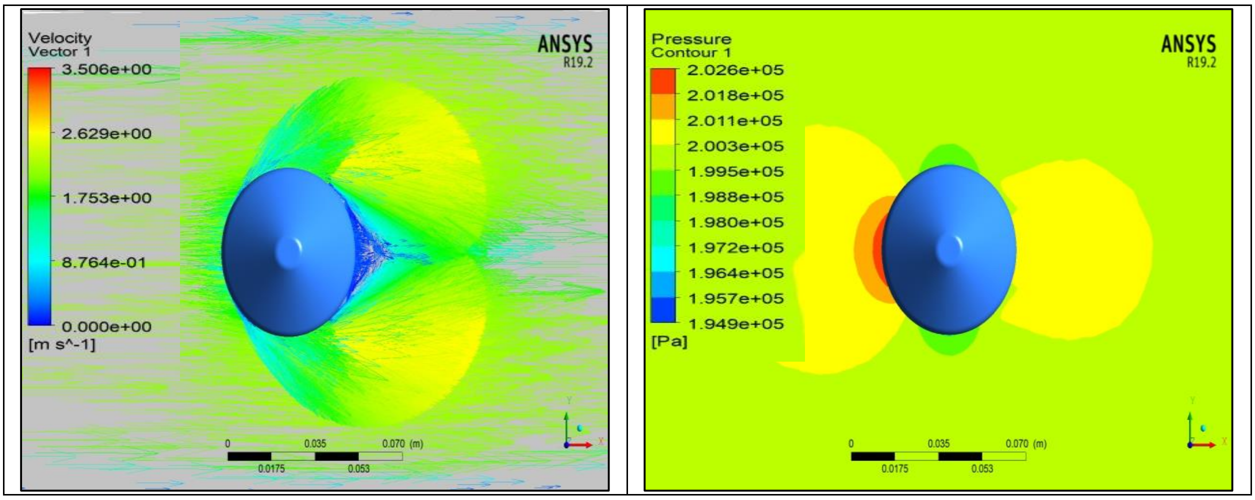


Fig. 6. The velocity vector and pressure distribution around the Design 2

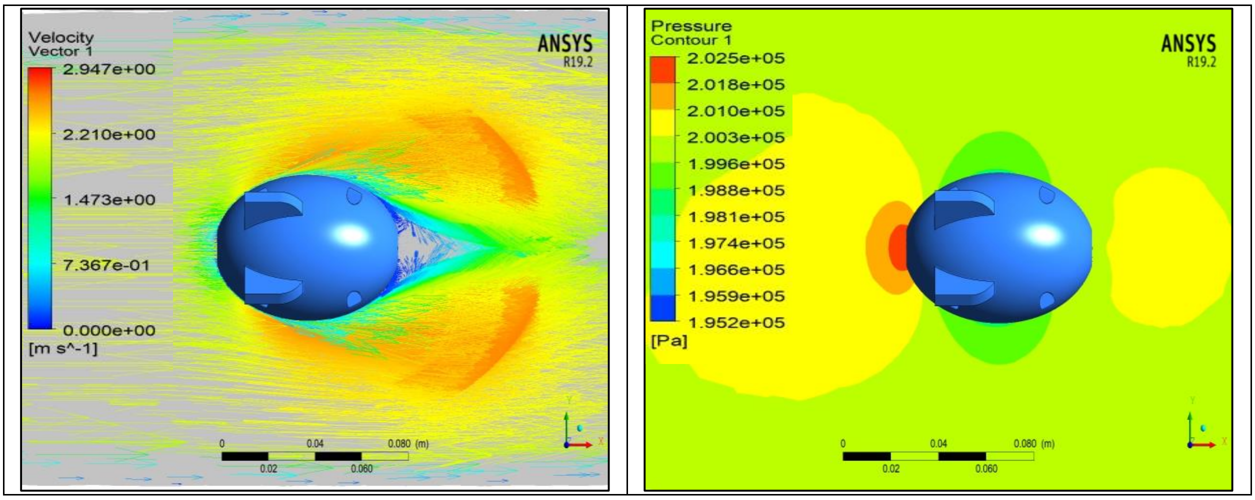


Fig. 7. The velocity vector and pressure distribution around the Design 3

4. Conclusions

Three different shapes of leakage sensors have been designed and analysed via CFD simulations. The best shape was the Design 3 where it produced the highest drag coefficient and hence will resulted in higher stability. Qualitative results show that all three cases have the ability to move inside the water pipeline network.

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