DRAG REDUCTION IN AXIAL FLOW IN A CONCENTRIC ANNULI SPACE AND A TUBE

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Abstract: *The drag reduction (DR) by injection of small amounts of polymers, surfactants and fibers in turbulent flow has been studied for over seventy years. The applications include transport of liquids in pipelines, firefighting operations, bio-medicine among many others. Up to now, the most part of the works is related flow in tubes, channels and rotating geometries. In fact, as far as we known, there is not any paper in which the drag reducing flow in an annular space has been considered and this is the main point of the present work. It is worth noting that the axial flow in annular space occurs in many industrial applications and it is relevant in several processes, as those in the drilling industry. Hence, in attempt to understand the main difference between the drag reduction in annular spaces in comparison to other geometries, specially that one observed in tubes, we conducted a sequence of experiments by aid of an experimental setup. We used different polymer solutions with different concentrations. Our main data are presented in terms DR over the number of pass through our system. By doing so, in addition to DR, we were able to take into account the fall of efficiency caused by mechanical polymeric degradation, which was displaced in terms of the relative drag reduction. Such a relative drag reduction is the current value of DR divided by its maximum value obtained at the first pass through the system.*
Keywords: *drag reduction, polymeric solutions, annular space, polymeric degradation*

1. NOMENCLATURE

a – Diameter ratio
c – Polymer concentration (ppm)
D – Hydraulic diameter (m)
D_c – Characteristic diameter (m)
D_i – Outer axis diameter (m)
D_o – Inner tube diameter (m)
DR – Drag reduction
f – Theoretical friction factor
f_{exp} – Experimental friction factor of the solution
f_o – Experimental friction factor of the solvent
M_v – Molecular weight (g/mol)
Q – Volumetric flow rate (m^3/s)
Re – Reynolds Number
V_o – Inicial volume (m^3)
t_i – Time on the instant "i"
$t*$ – Dimensioless time
Δp – Pressure drop (Pa)
μ – Fluid dinamic viscosity ($Pa.s$)
$\phi*$ – Form factor
ρ – Fluid density (kg/m^3)

2. INTRODUCTION

Many studies have been done to find a way to reduce the energy loss of a fluid flowing from one point to another with the injection of additives. These additives can be polymers, surfactants, cotton fibers, nylon and asbestos, paper pulps and gas bubbles. This paper studies the drag reduction by the addition of polymers. Toms (1949) was the first to observe that in turbulent flow in pipes, under certain conditions, the polymeric solutions require a lower specific energy related to the pure solvent. Beside the great impact of this effect on the basic studies of turbulence it also has a noteworthy contribution in solving enviromental problems or in making industrial process more cost-effective, as related by Gyr and Bewersdorff (1995).

According to Virk (1966), there are two situations using polymer additives: (i) it is possible to keep the same volumetric flow with a smaller pressure gradient; (ii) to achieve a greater volumetric flow with the same pressure gradient. Both situations are related to the pure solvent. The drag reduction induced by a series of equivalent polymers in a pipe is function of the concentration, the flow rate and the molecular weight; and the maximum drag reduction possible is limited by an asymptote which is independent of the polymer and the pipe size as related by(Virk, 1966, 1975).

The friction factor for a circular pipe is well known, but as studied by Jones Jr and Leung (1981), the correlations for circular pipes can not be used to an annulus space, since they have a dispersion from -25% up to 35% of the value. It was observed that the hydraulic diameter was not enough to describe exactly this behaviour and no correlation was accepted (Jones Jr and Leung, 1981). This disagreement is well known and has been the subject of many studies. From this, Jones Jr and Leung (1981) proposed the Colebrook correlation using a modified Reynolds number, reaching the dispersion of ±5% of the value, accepted for practical experiments.

This work aims to study the reduction of the friction factor in annular space and circular tube by adding rigid polymers, investigating the influence of the concentration of the polymer solution

3. LITERATURE REVIEW

The drag reduction is a phenomenon widely studied since the last century and was discovery as a reduction in the pressure loss of the flow of a turbulent flow at the same flow rate due to additives (Gyr and Bewersdorff, 1995). As quoted by Lumley (1969), to avoid confusion, the drag reduction is defined as the reduction of the friction factor in turbulent flow below that of the solvent. Algebraically, this definition can be written as shown in the Eq. (1).

$$DR(\%) = \left(\frac{f_o - f_{exp}}{f_o}\right) \times 100 \tag{1}$$

Toms (1949) noted that the reduction of the friction factor is more evident for a greater Reynolds number and that the phenomenon only occurs in the turbulent flow. Toms demonstrated that the additions of small amounts of polymers with high molecular weight in a fully developed turbulent flow would reduce the friction factor compared to solvent only (Silva, 2014).

Several studies about drag reduction have been made by Fabula (1971), Savins (1964), Metzner and Park (1964), Hershey and Zakin (1965), as quoted by Virk (1966), with many polymer solutions in turbulent flow through pipes with internal diameter of 0.5 to 5.0 cm. From these experiments, two general aspects have been recognized:

i. The start of the drag reduction occurs in a well-defined manner; and

ii. Qualitatively, the drag reduction increases with the Reynolds number, with the molecular weight of the polymer and, within limits, with the concentration.

Despite several studies, many questions are not answered yet, among them, the interaction of the polymer and the vortexes caused by turbulence (Silva, 2014). As reported by Lee (2010), two theories have been proposed to explain the drag reduction phenomenon, one is related to viscous effects, called the theory of viscous forces proposed by Lumley (1969), and the other is the elastic theory, proposed by Tabor and De Gennes (1986).

In viscous forces theory, the drag reduction is attributed to additional dissipation introduced by the polymer (Lumley, 1973), it means, the polymers act directly on the vortexes created by turbulence. According to Tabor and De Gennes (1986), as proposed in the elastic theory, the kinetic energy of the vortexes is entirely converted into elastic energy by the polymer, then this energy is transferred to the flow. The elastic theory is quite reasonable when it comes to flexible polymer, but does not appear consistent when considered rigid polymers. The viscous forces theory(Lumley, 1969) perhaps best explain the phenomenon with such rigid materials.

3.1 Used additives

The additive used in this work is the flexible polymer polyethylene oxide (PEO) with a molecular weight equals to 7×10^6 g/mol. Due to the concentration used in the solutions they do not have pseudoplastic characteristics and the fluids were modeled as newtonian fluids.

3.2 Influence parameters

According to Fox and McDonald (1984), the distributed pressure losses can be calculated both for laminar and turbulent flow, but in turbulent flow it is not possible to evaluate the pressure drop analytically in the fully developed flow. So, the experimental data and the dimensional analysis are used to correlate them. In fully developed turbulent flow, the pressure drop Δp, due to friction, on a horizontal pipe of constant area, depends on the pipe diameter, *D*, on the length, *l*, on its roughness, *e*, on the mean velocity of the flow, *V*, on the fluid properties as density, ρ, and viscosity, μ, as shown in Eq. (2).

$$\Delta p_{rough\ tube} = \phi(D, l, e, V, \rho, \mu) \tag{2}$$

For a smooth tube, the roughness can be neglected and the pressure drop can be described as a function of D, l, V, ρ and μ, Eq. (3).

$$\Delta p_{smooth\ tube} = \Delta p = \phi(D, l, V, \rho, \mu) \tag{3}$$

Using the Buckingham's Pi Theorem, the dimensionless groups that can be used to correlate the data are shown in Eq. (4).

$$\frac{\Delta p}{\rho V^2} = \phi\left(\frac{\mu}{\rho V D}, \frac{l}{D}\right) \tag{4}$$

Developing the Eq. (4), and knowing that the pressure drop is directly proportional to the third dimensionless group, the pressure loss, Δp (Pa), can be written as the Eq. (5).

$$\Delta p = f \frac{l}{D} \frac{V^2}{2} \rho \tag{5}$$

Where f is the Darcy friction factor. Thus, the experimental friction factor is obtained from Eq. (6).

$$f_{exp,tube} = \frac{2D\Delta p}{V^2 l\rho} \tag{6}$$

It is important to note that D is the hydraulic diameter. So, the experimental friction factor for annulus space may be calculated as shown in the Eq. (6).

$$f_{exp,annular} = \frac{2(D_o - D_i)\Delta p}{V^2 l\rho} \tag{7}$$

Jones Jr and Leung (1981) believes that the behavior described by the flow into an annulus space is similar to the flow in a circular pipe and the Colebrook correlation can be used with the same Reynolds number definition, Re. The theoretical friction factor can be found by Eq. (8), and the Reynolds is found by Eq. (9), where D_c is the Characteristic dimension.

$$\frac{1}{\sqrt{f}} = 2\log_{10}(Re\sqrt{f}) - 0.8 \tag{8}$$

$$Re = \frac{\rho V D_c}{\mu} \tag{9}$$

The characteristic dimension can be found by Eq. (10), according to Jones Jr and Leung (1981).

$$D_c = [D_o(1-a)]\phi^* \tag{10}$$

Where ϕ^* is the form factor, Eq. (11), and a is the diameter ratio, Eq. (12).

$$\phi^* = \frac{1}{(1-a)^2}\left[1 + a^2 - \frac{1-a^2}{\ln\left(\frac{1}{a}\right)}\right] \tag{11}$$

$$a = \frac{D_i}{D_o} \tag{12}$$

To analyze the drag reduction in a loop it is used the dimensionless time, Eq. (13). The dimensionless time represents the number of times that the initial volume of the fluid pass through the loop. Where V_o is the initial volume, Q is the volumetric flow rate and t_i is the time on the instant "i".

$$t^* = \frac{Qt_i}{V_o} \tag{13}$$

4. METHODOLOGY

This section details the sample preparation procedure and the experimental setup.

4.1 Sample preparation

The sample is prepared in a closed container. The poly(ethylene) oxide is weighted according to the desired concentration and then it is placed on the water and the solution is solubilized by brownian motion for 48 hours. After this time, the sample is placed in the tank and the test begin.

4.2 Experimental setup

An experimental assembly is used to determine the friction factor, consisting of a closed circuit to ensure the circulation of the fluid, according to the model shown in Fig. (1). The elements of the assembly are: one frequency inverter CFW- 08 -RS-485, one magnetic type flow meter (1) and three pressure transducers Warme with 0.01% uncertainty. The assembly is fixed to a wooden frame (2) attached to a metal frame. The prepared solution is stored in a stainless steel tank (3). The suction of the fluid (4) is made by using a screw pump Weatherford (5), model WHT40F.

Two pressure accumulators (6) are in the pump discharge to reduce the pulsation of the flow caused by the pump. It is importante to note that the horizontal and vertical lenghts are sufficient to ensure a flow entirely developed in the pressure drop measurement region (7) as well as the flow measurement region (1). The fluid is pumped into the test pipe through a hydraulic hose with *1"* diameter (8).

Flange connections were used to connect the pipes and to facilitate the exchange of pipes. A sample of working solution can be collected for later analysis through a valve positioned after the measuring section of the pressure (9). The return pipe was dipped in the tank approximately 30 cm to avoid the fluctuation of the air-liquid interface in the tank and to prevent the formation of air bubbles. The temperature of the tank is adjusted from the flow of a secondary fluid coming from a thermostatic bath Lauda Proline RP1845, flowing through a copper coil mounted inside the tank. The experiment is controlled by a supervisory system developed under the platform LabView 2010 and the communication is made by an industrial network.

The temperature of the fluid present in the tank is obtained from an average of four T-type thermocouples mounted in the tank. The temperature signal from these thermocouples is acquired by a data acquisition card NI 4351 in order to assist the control of the temperature of the fluid in the tank.

The friction factor is obtained from the static pressure measurements obtained in three interchangeable points. For these measurements, it was performed eleven holes of 2.0 mm diameter and with a distance of 100.00 mm between their respective centers. A stainless steel tube with a diameter of *1/8"* and a length of 30 mm was welded in each hole for assembling the hoses to connect the pressure transducers. The pressure signal is acquired by the NI-6251 data acquisition board. A honing process was also done to guarantee the internal diameter of the pipe after the welding process of the pressure outlets, ensuring constant and known diameter.

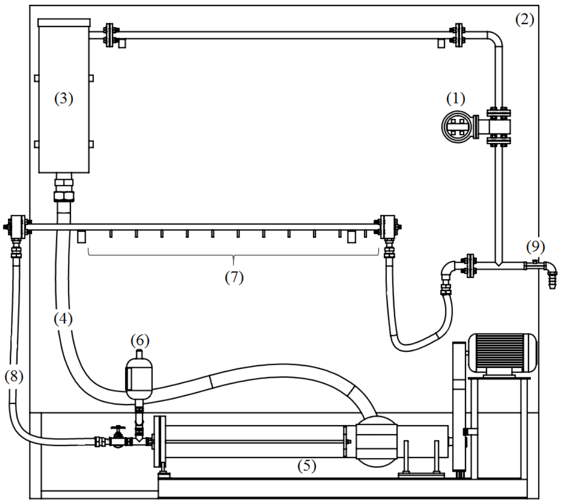

Figure 1: **Schematic figure of the experimental setup.**

4.3 Experimental validation

To begin the tests in both geometries, the annular space and the circular tube, it is necessary to validate the experimental setup, in other words, to check if the experimental friction factor value aproximates the theoretical. To do so, various tests were made with water. Figure (2) shows the results of these tests for the circular tube and Fig. (3) for the annular space. Through the figures it is possible to see that the experimental results has high concordance with the theoretical data. The maximum error is about 5% for both geometries. The concentric annular space used have the diameter ratio equals 0.231 ($a = 0.231$).

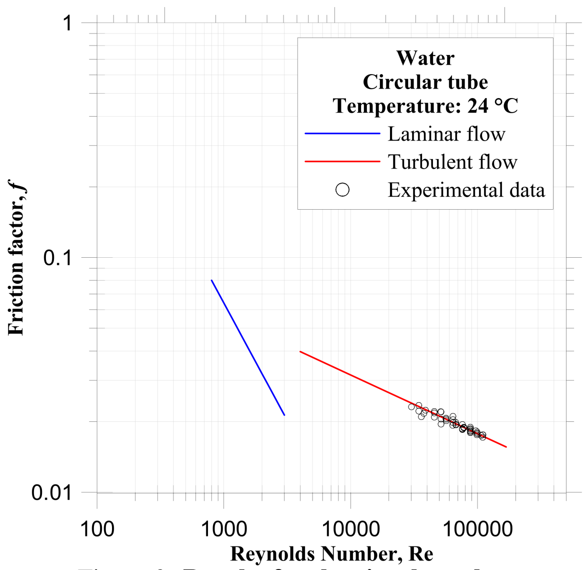

Figure 2: **Results for the circular tube.**

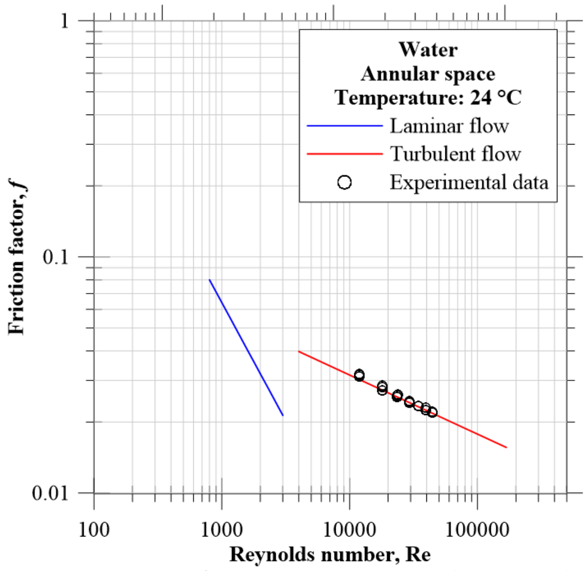

Figure 3: **Results for the annular space** ($a = 0.231$)**.**

5. RESULTS AND DISCUSSION

The main results are presented in terms of drag reduction, $DR(\%)$, as a function of the dimensionless time, t^*. All our tests were conducted at a fixed volumetric flow rate. As mentioned before, the drag reduction is analyzed taking into account the friction factor of the polymeric solution for each t^* and compared with the solvent one in the same Reynolds number, Re.

Figures (4) and (5) show the drag reduction ($DR(\%)$) as a function of the dimensionless time (t^*) for the circular tube and annular space for the solution of PEO, with $M_v = 4.6 \times 10^6$ g/mol. The concentration was varying from 25 until 200 ppm while the temperature and volumetric flow rate were fixed. For both cases, the drag reduction decreases until a minimal value and higher the concentration the greater the drag reduction, such as the results reported by Kenis (1971), Vanapalli *et al.* (2006), Pereira and Soares (2012), Pereira, Andrade and Soares (2013), Silva (2014) and Sandoval (2015). The data analyzed show the same phenomenon, $DR(\%)$ increases with the addition of concentration independent of the geometry. Besides the maximum drag reduction, region (I), other region of interest is where the drag reduction decreases significantly less with time, this region is called the drag redution asymptote(II).

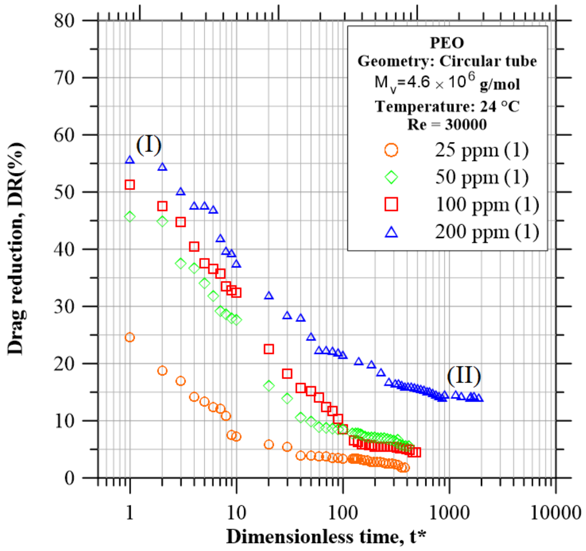

Figure 4: **Results with the circular tube.**

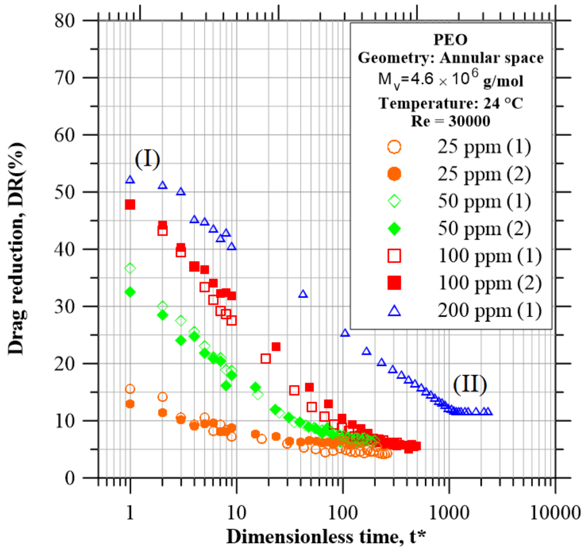

Figure 5: **Results with the annular space.**

Figures (6), (7), (8) and (9) show the comparisson of the results shown in Fig. (4) and (5) for each concentration, 25, 50, 100 and 200 ppm, respectively. Each figure shows the degradation of the solutions, therefore, at the end of the test the solution still shows some drag reduction compared to the solvent, in this case the solvent is water. As reported by Pereira and Soares (2012), the degradation causes the decrease of the polymer molecular weight reducing the drag reduction.

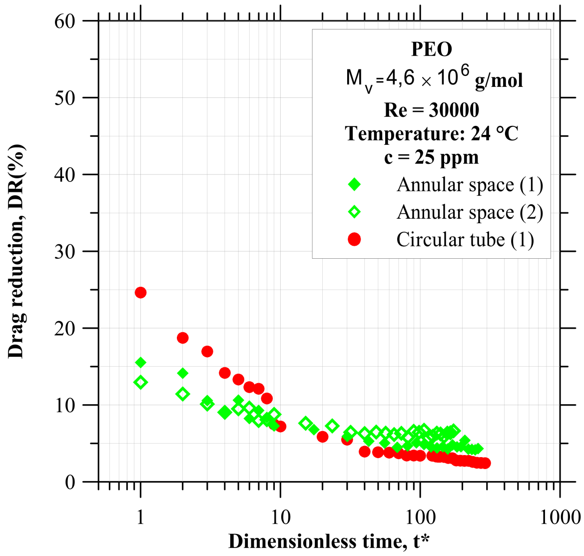

Figure 6: **Comparisson between the drag reduction for a circular tube and an annular space using PEO at 25 ppm.**

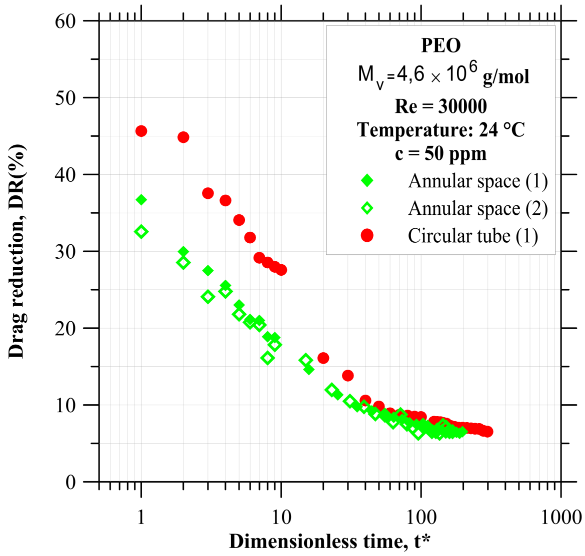

Figure 7: **Comparisson between the drag reduction for a circular tube and an annular space using PEO at 50 ppm.**

Is important note that the 200 ppm concentration reached the maximum values of DR, as expected. For the 25 ppm and 50 ppm concentrations, the circular tube show a higher DR at the beginning, for the last two concentrations, the solution show the same behavior, independent of the geometry used.

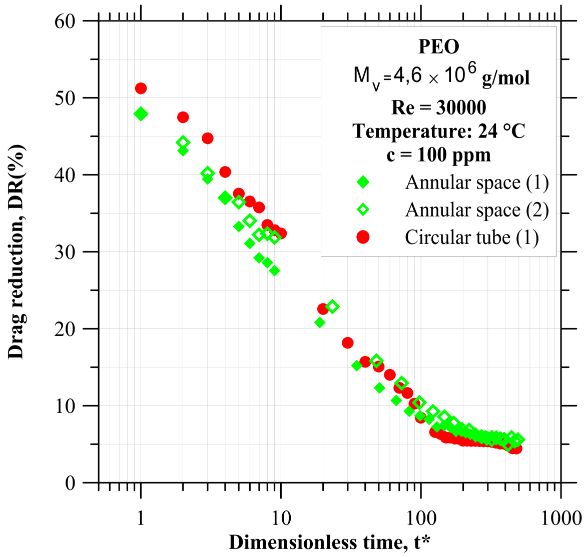

Figure 8: **Comparisson between the drag reduction for a circular tube and an annular space using PEO at 100 ppm.**

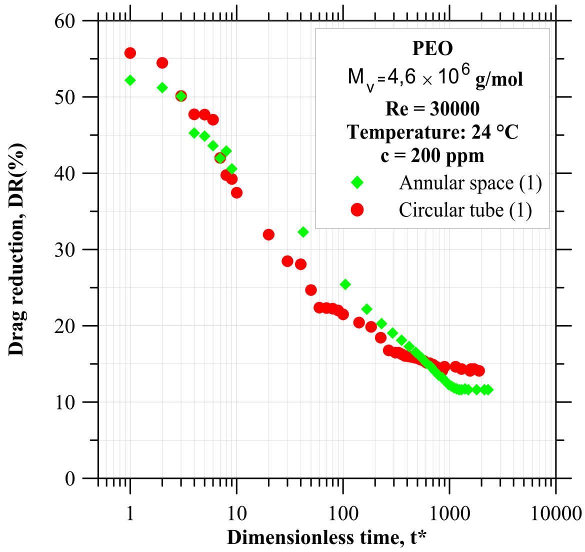

Figure 9: **Comparisson between the drag reduction for a circular tube and an annular space using PEO at 200 ppm.**

6. FINAL CONSIDERATIONS

We present an experimental approach developed to analyze the drag reduction behavior in differents geometry. The tests were carried out with solutions of Poly(ethylene) Oxide (flexibe polymer) for differents concentrations. It was observed high concordance between experimental tests and theory. The experimental and theoretical data had a maximum dispersion of 5% for both geometries. It is noteworthy that the tests realized with the polymer solutions illustrate the effects of the concentration and the geometry in the drag reduction phenomenon. The polymer degradation was computed using a approximate number of times that the initial volume pass through the circuit at a fixed volumetric flow rate.

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