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NEW FRICTION FACTOR CORRELATION FOR THE MIT REACTOR FUEL ELEMENTS

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ABSTRACT

The MIT Research Reactor (MITR) is the only research reactor that utilizes plate-type fuel elements with longitudinal fins to augment heat transfer. Recent studies on the conversion to low-enriched uranium (LEU) fuel at the MITR proposed fuel design with a smaller coolant channel gap than the existing HEU fuel. Therefore the friction factor for the finned rectangular channels needs to be verified experimentally. In this study the friction coefficients were measured in a flow loop for both laminar and turbulent flow regimes. The friction pressure drop experiment was designed for static differential pressure measurements for both smooth and finned rectangular coolant channels of various gap sizes. Experimental data showed that the friction factors of turbulent and laminar flows in smooth rectangular channels are in good agreement with existing correlations. For turbulent flow, a new correlation has been proposed for the finned coolant channels. The new friction factor correlation is similar to the Blasius correlation but with a different constant to account for the increased surface roughness.

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1. Introduction

The first MIT Research Reactor (MITR-I) was a heavy water cooled and moderated reactor with an open array of plate-type fuel elements. It attained criticality in 1958 and operated up to 5 MW until 1973. The reactor core of the MITR-I was later modified to optimize the thermal neutron flux in the reflector region where the experimental beam ports are located. The MITR-II, which began operation in 1975, is a light water cooled and moderated, heavy water reflected reactor that is licensed to operate up to 5 MW. The reactor utilizes flat, plate-type fuel elements with 93% high enrichment uranium (HEU), and produces a high quality neutron flux for interdisciplinary research in the areas of advanced fuel and material for nuclear energy systems, neutron science, nuclear medicine, and radiation science and technology. It provides a wide range of experimental facilities and serves as a unique resource for users from both within and outside the MIT community.

The hexagonal core of the MITR-II contains 27 fuel element positions in three rings. The inner-most ring, or the A-ring, contains 3 positions; the B-ring contains 9 positions and finally the C-ring, the outer-most ring, contains 15 positions. The 27 fuel element positions are normally filled with 24 fuel elements, leaving 3 positions available for solid dummy elements and/or in-core irradiation facilities. Owing to power peaking concerns, two solid aluminum dummy elements are often located in the central A-ring where the neutron flux is highest. The overall length of a fuel element, including the end nozzles, is 26.25”. Each fuel element consists of fifteen 23” long fuel plates assembled between two 0.188” thick side plates. Held by the side plates, each fuel element consists of 14 full flow channels and 2 half-channels. The base-to-base channel height, here defined as the distance between the fin bases of two opposing finned rectangular fuel plates, is 0.098” in the inner coolant channel. The fuel plates are 0.080” thick with 110 continuous longitudinal rectangular fins on both sides. The fin dimension is 0.010” high, 0.010” wide and 0.010” apart from one another. Figure 1 is a schematic of the fuel element cross section. Currently, each fuel plate contains 33.7 grams of 93% enriched HEU in the form of an aluminide (UAl_x) cermet matrix. The thickness of the fuel meat is 0.030”, and the thickness of aluminum alloy cladding is 0.015”.

To remove heat generated in the reactor core, light water as the primary coolant enters the reactor core tank through the inlet plenum. It flows through the annular region between the core tank and the core shroud, followed by the six flow channels around the hexagonal core support housing assembly. The primary coolant is then directed upward and distributed through the coolant channels in the fuel elements, flow guide, core support housing assembly, outlet plenum, and finally to three coolant pipes exiting the core tank. Fission energy is removed from the primary coolant to the secondary coolant through heat exchangers.

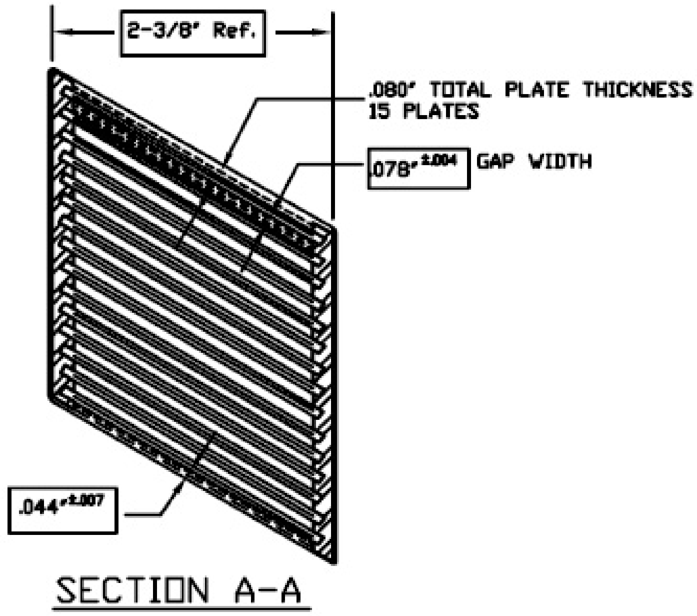

Figure 1: Cross section of the MITR-II fuel element.

2 Proposed LEU Fuel and Mixed LEU/HEU Core Conversion Strategy

Studies on the utilization of LEU fuel at the MIT Reactor have been performed previously by Gehret [1] and more recently by Newton et.al. [2]. It was concluded that should high density LEU fuel become available, the MITR-II can be converted from HEU fuel to LEU fuel while maintaining an equivalent or higher neutron flux for experiments [2]. It is also suggested that the refueling interval of the reactor core with LEU fuel can be about twice longer than that with HEU fuel at the current reactor thermal power of 5 MW. The monolithic uranium-molybdenum (U-Mo) fuel is currently the only viable option for LEU fuel with sufficient uranium density to be used in the MITR. Currently, an LEU design for the MITR is proposed using high density monolithic U-Mo fuel with molybdenum content of 10%. This fuel has a uranium density of 17.5 g/cm^3. Use of fuels with higher molybdenum content (therefore with a slightly lower uranium density) is also possible. It was suggested that the addition of a percentage or two of molybdenum will have little effect on neutronic performance [2]. Thermal hydraulic analyses in support of the LEU fuel design were performed recently by Ko et. al.[3,4]. In the design of the LEU core, thinner fuel meat and cladding are used in the fuel plates. Through a thermal hydraulic optimization study, the LEU fuel element design containing 18 fuel plates is selected while maintaining the same outer fuel element geometry. Each finned rectangular fuel plate contains a 0.020" thick fuel meat, with 0.010" thick cladding on both sides. Similar to the HEU design, longitudinal fins of 0.010" by width, 0.010" by height, and 0.010" apart from one another exist on the cladding surface. The increase in the number of fuel plates per element in the proposed LEU core design reduces the gap width of the flow channels, which is slightly offset by the reduced thicknesses of the fuel meat and the cladding. The base-to-base channel gap decreases to about 0.092" as compared to 0.098" in HEU fuel element [8, 9]. The conversion process of the MITR is likely to be a gradual transition with mixed LEU and HEU fuel elements. There are several benefits of this transitional core conversion strategy:

(1) Only a few fresh LEU elements will be inserted in each transitional core. This reduces the burden of receiving, inspecting, and storing a large number of new fuel elements during a given refueling cycle.

(2) The excess reactivity due to gradual addition of new fuel elements is more manageable than a fresh LEU core.

(3) The initial LEU fuel elements will be inserted in the B-ring positions of lower power peaking to allow for monitoring the performance of this first-of-its-kind LEU fuel element. In the event of a failure, the core configuration can be returned to HEU core to minimize its impact on the reactor utilization program.

(4) Since each spent fuel shipment is limited to eight elements due to the capacity of the spent fuel shipping cask, gradual discharge of the HEU fuel will minimize the number of HEU fuel elements stored in the spent fuel pool which is the current practice of the MITR fuel management plan.

From the operational perspective, thermal hydraulics operation limits of the HEU core and the LEU core are governed by the respective safety analysis reports that are approved by the US Nuclear Regulatory Commission. The main challenges associated with transitional core operation are in the determination of nuclear power peaking and primary flow distribution through the core region for each mixed core configuration. These should be considered carefully within the context of the established HEU and LEU core operating limits in order to ensure that pertinent licensing requirements are met.

3. Pressure Drop Experiment

A friction pressure drop experiment was designed and constructed at the MIT Nuclear Reactor Laboratory to obtain experimental data of friction factors in rectangular coolant channels with fins of the same geometry of the MITR fuel element. The experiment loop contains an aluminum water bath, cover, upstream plenum, downstream plenum, lift, two flat or finned plates that form the coolant channel, two spacers, and rubber gasket. The test assembly is entirely made of aluminum alloy for ease of machining. Figure 2 is a schematic diagram of the pressure drop loop.

The test section region consists of two flat or finned plates, and two aluminum spacers that determine the size of the gap between the plates. The plates and the spacers are made of Al-6061 alloy. The single-sided finned plates, provided by the Idaho National Laboratory, are arranged with their longitudinal rectangular fins facing each other to imitate the flow channel between two MITR fuel plates. The finned plates are 0.250” thick, with 110 fins spacing on each finned surface. The height of the spacers determines the base-to-base channel height between the finned plates and, thus, the aspect ratio and hydraulic diameter of the flow channel. The static pressure is measured at 12" from the inlet coolant channel region to allow for the flow to become fully developed. The total length of the pressure drop measurement is 24".

De-ionized water enters the front end of the test assembly via the 0.5" NPT inlet into the upstream plenum, the rectangular coolant channel and the downstream plenum, before de-ionized water exits via the 0.5" NPT outlet on the back end of the test assembly. To collect the data of pressure drop measurements in rectangular ducts with fins, four 0.125" NPT static pressure taps of 0.350" deep, with concentric through holes of 0.025" diameter, are made on the two sides of the test assembly. Each pair of static pressure taps is connected to a differential pressure transducer to measure the pressure drop in the test section.

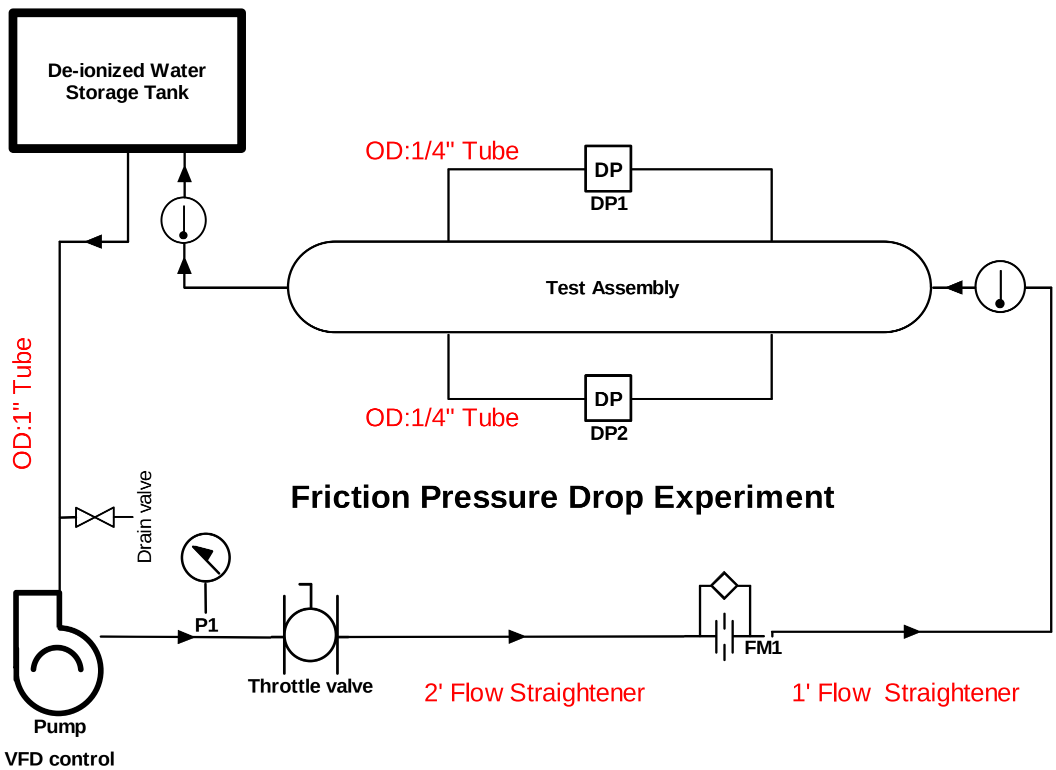

Figure 2. Schematic diagram of experiment loop for friction factor study.

Figure 3. Al-6061 plate with 110 continuous longitudinal rectangular fin spacing fabricated by Idaho National Laboratory.

Figure 4. Test assembly consists of two single-sided finned plates separated by two spacers.

4. Experimental Results and Analysis

Friction pressure drop can be calculated using the following equation:

$$\Delta P = f\frac{L}{De}\frac{1}{2}\rho v^2 \qquad (1)$$

where ΔP is the friction pressure drop, f is the friction factor, L is the coolant channel length, De is the equivalent diameter, ρ is density, and v is flow velocity. The equivalent diameter is calculated by:

$$De = \frac{4A}{Pw} \qquad (2)$$

where A is the flow area and Pw is the wetted perimeter.

Friction factor f relates the pressure gradient to the kinetic head based on the average velocity and the channel equivalent diameter. Friction factor of fully developed laminar flow in circular tube was solved analytically using the continuity equation and the momentum equation [5]. It leads to a special condition that is often applied to fully developed laminar flow, that the product of laminar friction factor and Reynolds number $(f\,\mathrm{Re})$ is a constant that depends on the geometry of the channel, as proposed in Ref[6]:

$$f = \frac{64}{\mathrm{Re}}\text{, for circular ducts, and} \qquad (3)$$

$$f = \frac{96}{\mathrm{Re}}\text{, for infinite parallel plate channels.}$$

where the Reynolds number is defined as $Re = \frac{\rho v D_e}{\mu}$ and μ is the fluid viscosity.

For developed laminar flow in rectangular channels of non-zero aspect ratio, the friction factor correlation is given in [7,8] as follows:

$$f = \frac{96}{\mathrm{Re}}\left[1 - 1.3553\beta + 1.9467\beta^2 - 1.7012\beta^3 + 0.9564\beta^4 - 0.2537\beta^5\right] \qquad (2)$$

where β is the aspect ratio of the rectangular channel. The aspect ratios for 0.098” and 0.092” gap widths are 0.043 and 0.040, respectively. These ratios reduce the constant from 96 to approximately 91.

The above equations are used to describe the friction factors for laminar flows, often with $\mathrm{Re} \le 2000$, and are independent of wall roughness [9].

Turbulent flow generally occurs when inertial force is dominant. It generates random eddies, vortices and other flow fluctuations that destroy the laminar flow lines. Turbulent flow in smooth tubes occurs at high flow rates, at which Reynolds numbers are high. A commonly encountered expression for friction factor for turbulent flow in tubes is the Karman-Nikuradse equation [5], where the friction factor f is predicted as follows:

$$\frac{1}{\sqrt{f}} = -0.8 + 0.87\ln\left(\mathrm{Re}\sqrt{f}\right) \tag{3}$$

Owing to the difficulty in using the Karman-Nikuradse equation in practice, simplified relations, such as the Blasius and the McAdams equations, are often used to calculate the friction factors for turbulent flows in smooth circular conduits. The Blasius equation is used extensively, to predict the friction factor for turbulent flow with $\mathrm{Re} < 30{,}000$ in smooth tubes [5]:

$$f = 0.316 \cdot \mathrm{Re}^{-0.25} \tag{4}$$

The McAdams equation is used for turbulent flow of higher Reynolds number, $30{,}000 < \mathrm{Re} < 10^6$, in smooth tubes [5]:

$$f = 0.184 \cdot \mathrm{Re}^{-0.2} \tag{5}$$

The friction factor correlation for flow in smooth circular tubes can similarly be derived for other geometries. It is, however, argued in Ref [5] that the velocity gradient of turbulent flow is primarily near the channel wall, and geometries tend to have little influence on the friction factor. Moody's chart [10] is also used extensively to determine the friction factors for turbulent and laminar flows in pipes of different surface roughness.

In the analysis of experimental data of finned rectangular channels, two approaches are attempted in the calculation of the equivalent hydraulic diameters. The first approach treats the rectangular fins as a form effect in the calculation of the total perimeter P_w^{finned}.

$$P_w^{finned} = \left[w_{ch} + h_{ch} + \left(2n_f\right)\cdot h_f\right]\cdot 2 \tag{6}$$

where w_{ch} is the width of the flow channel, h_{ch} is the base-to-base height of the finned flow channel, h_f is the height of a rectangular fin, and n_f is the number of continuous longitudinal rectangular fins on each plate. In the second approach, the fins are treated as a roughness effect and therefore the wetted perimeter is about half of that for finned surface. The equivalent hydraulic diameter of finned channel is approximately half of that of a smooth rectangular channel. Using Eqs.(1) and (2), it can be derived that assuming constant flow velocity the friction pressure drop is proportional to $De^{-1.25}$. Therefore a factor of two difference in the equivalent diameter would yield a 138% discrepancy in friction pressure drop. Initial experimental data of finned coolant channel showed that by the finned equivalent diameter and the Blasius correlation significantly over-estimated the friction pressure drop, This raises the concern that it may result in significant over-estimate of the friction pressure drop if the existing. Hence, the second approach of using smooth channel equivalent diameter is adopted in the data analysis. To model the roughness effect, the a new coefficient in Eq.(6) is determined empirically using experimental data.

Figures 5 and 6 provide comparisons of measured friction factors for laminar and turbulent flow regime, respectively. The measurements are represented using Re number based on smooth channel equivalent diameter. As shown in Figure 5, finned and smooth rectangular channels generally follow the same trend which confirms that the fins do not have a significant effect on viscous pressure loss for laminar flow. This validates the assumption that the fins in fact results in surface roughness effect, not a form effect. As shown in Figure 6, the measured turbulent friction factors in a smooth rectangular channel are in good agreement with the Blasius correlation. For finned channels, using the smooth equivalent diameter, the measured friction factors are much higher which is consistent with a higher surface roughness. As such, a new correlation for the friction factor is proposed for turbulent flow for finned rectangular channel. The new correlation uses the same exponential as the Blasius correlation. It is then multiplied by a constant determined through curve-fitting of experimental data which is given as follows:

$$f_d = 0.575 \cdot \mathrm{Re}_s^{-0.25} \tag{9}$$

The new constant is 82% higher than that in the Blasius equation which was developed for smooth tubes.

Using the uncertainties of individual parameter, the uncertainty in the friction factor can be quantified via the method of error propagation [11]. The percentage uncertainty from the measurements of friction factor f_d is estimated to about 15% for both laminar and turbulent flows [12].

5. Conclusions

Experiment data show that the laminar friction pressure drop is unaffected by the presence of the longitudinal fins. This is consistent with the theory that friction factors are independent of surface roughness for laminar flow. For turbulent flow, a new correlation for the friction factor has been proposed. The new friction factor correlation uses the smooth channel equivalent diameter, the same exponent as the Blasius friction factor, and is multiplied by a coefficient that is determined through curve-fitting of experimental data. The new coefficient is 82% higher than that in the Blasius equation which was developed for smooth tubes. For the assessment of pressure drop of the MITR fuel, equivalent hydraulic diameters of smooth rectangular coolant channels should be applied for both laminar and turbulent flow regime.

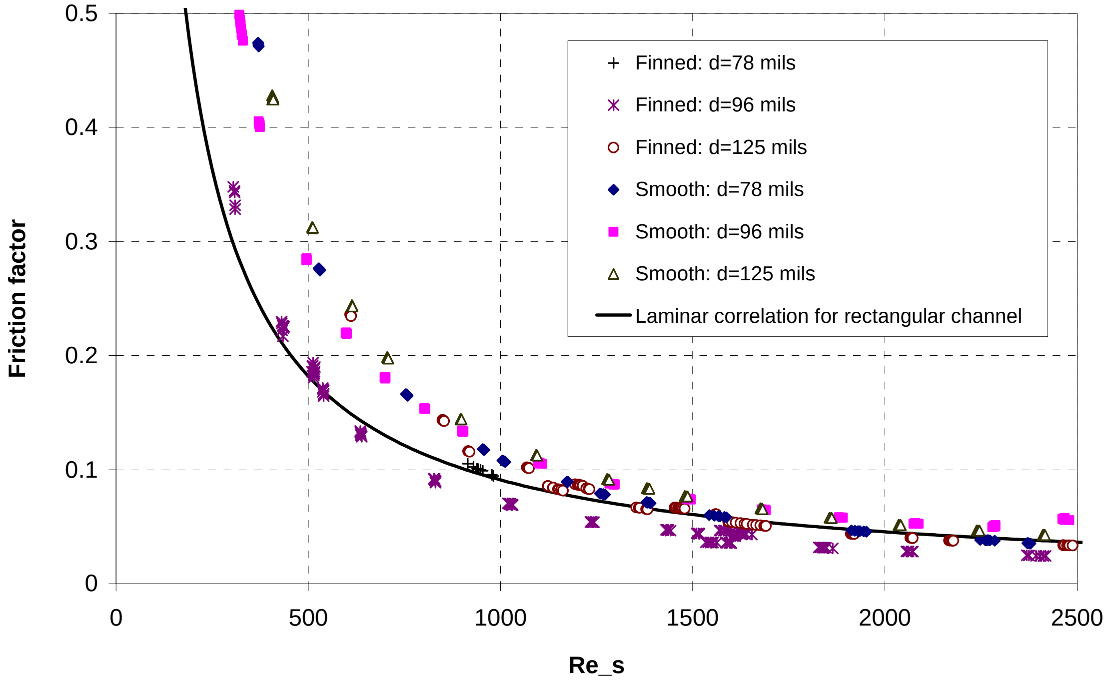

Figure 5. Comparison of measured friction factors for laminar flow in smooth and finned rectangular channel.

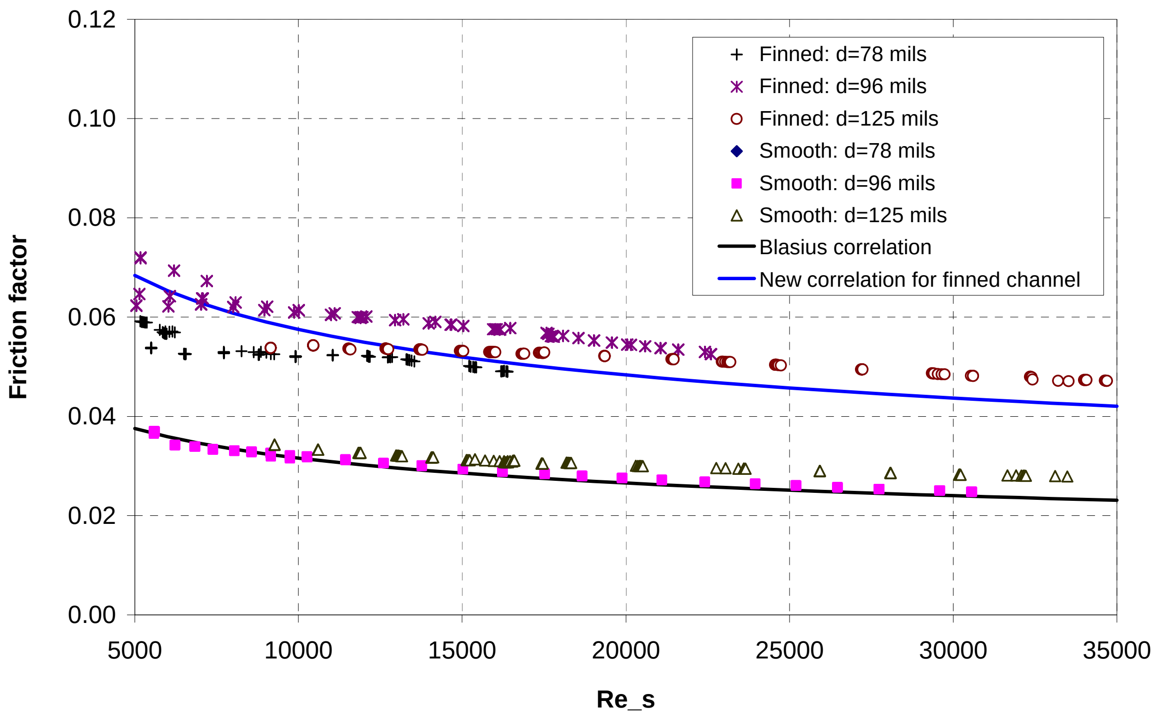

Figure 6. Comparison of measured and predicted friction factors for turbulent flow in smooth and finned rectangular channel.

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