Cavitation in Fractal Geometry Orifices

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Abstract

An experimental research of three types of orifices was carried out in a hydraulic circuit. One-hole orifice and two fractal-shaped orifices (von Koch snowflake, Apollonian gasket) were tested. Fractal-shaped orifices had lower pressure loss in non-cavitating regime. For cavitating conditions, von Koch snowflake orifice maintained the reduced pressure loss, while pressure loss curve within Apollonian gasket orifice gradually aligned with that of one-hole orifice. Dynamics of the cavitating flow behind the orifices featured distinct peak for one-hole orifice connected with shedding of one strong coherent vortical structure, while pressure amplitudes for fractal-shaped orifices (especially von Koch snowflake orifice) were significantly lower. This conclusion is attributed to multiscale behavior of the flow behind the fractal-shaped orifices.

Keywords: cavitation; orifice; fractal; pressure loss; noise; von Koch snowflake; Apollonian gasket

Introduction

Orifices are frequently used in many industries for flow measurement (thermal and nuclear power plants, water pipelines), flow restriction (process and chemical plants), but also in multiphase flow reactors to enhance mixing [1, 2]. Their advantage is very simple design and manufacturing. In many situations, in severe conditions, cavitation occurs. This is very often connected with significantly increased level of noise and vibrations [1].

Orifices can also serve as a simple model to study cavitation in valves. Standard orifices have one circular hole with prescribed thickness/diameter ratio and shape of the orifice edge.

In our previous research [3, 4], it was found out that pressure amplitudes downstream of both one-hole and multihole orifices are lower than those generated by Venturi tube.

Fractal geometry

While one-hole orifices are mostly used in practice, investigations have also been carried out on multihole orifices [2, 4]. It was proved that they can achieve lower pressure loss across the orifice. Both one and multihole orifices are manufactured with sharp and smooth edges.

However in nature most of the objects are characterized by fractal shape (leaves, feathers, roots, etc.) By definition fractal objects are those, where each part has the same statistical character as the whole. It means that some geometrical pattern is replicated on different scales and self-similarity is established. Attention to this feature of natural objects was especially brought by Mandelbrot [5]. Until recently there was no practical utilization of fractal shapes in fluid mechanics and technologies related to fluids handling. Seoud and Vassilicos [6] performed extensive investigations on turbulence generated by fractal objects and wakes behind the fractal shaped objects. They concluded that fractal shaped objects provide unique homogeneous isotropic decaying turbulence and might be used for passive multiscale control of the turbulent flow. Kearney [7] suggested practical application of fractals for improvement of the flow processes to control formation of the fluid structures for example in sugar industry. Aly et al [8] and Manshoor et al [9] applied fractal shapes to orifice plate edges. Aly et al designed and experimentally tested in wind tunnel fractal-shaped orifices based on von Koch snowflake (up to the fourth generation of fractality). Manshoor et al experimentally tested in hydraulic circuit an orifice with several sets of holes with fractally scaled diameters. All these investigations have shown improved performance of fractal-shaped orifices in terms of pressure loss compared to one-hole orifice. Later a CFD study was performed by Elsaey et al [10] using the shapes from [8].

However no information is provided in above mentioned papers about the dynamics of the flow through fractal-shaped orifices (i.e. frequency of the dominant pressure amplitudes) and about the cavitation within these orifices.

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Design of fractal shaped orifices

One-hole orifice with hole diameter 24 mm placed in a pipe with inner diameter 50 mm is reference case for the present study. Two types of fractal-shaped orifices are designed with the same flow cross-sectional area as one-hole orifice. The first type is based on von Koch snowflake. Derivation of this shape is illustrated in figure 1. It is formed by gradual dividing of a line into three parts and forming a triangle above the middle part. The fractal dimension of such object is 1.2619. Less known fractal shape, which is axisymmetric, is Apollonian gasket formed by so called Sode's circles. This object is made of a set of holes with scaled diameters.

In our study the third generation of von Koch snowflake was manufactured from plastic material by rapid prototyping (see figures 2, 4). Apollonian gasket was made by boring holes into plastic material plate (see figures 3, 4).

The minimum length scales for both fractal-shaped orifices, which are based on the shortest edge or smallest diameter of the hole respectively and maximum length scales which are based on largest gap within the orifice are summarized in table 1.

One-hole orifice was manufactured from stainless steel plate. The diameter/thickness ratio for one-hole orifice and von Koch snowflake orifice is 0,46, for Apollonian gasket orifice ranges from 0.96 to 0.09.

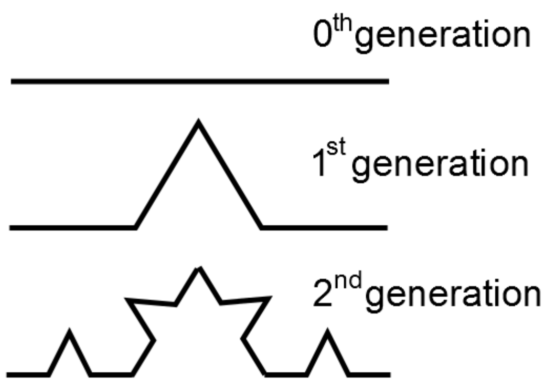

Figure 1. Fractal shape generation for von Koch curve

	von Koch snowflake	Apollonian gasket
L_{min} (mm)	30.67	11.50
L_{max} (mm)	2.95	1.00

Table 1. Length scales in fractal-shaped orifices

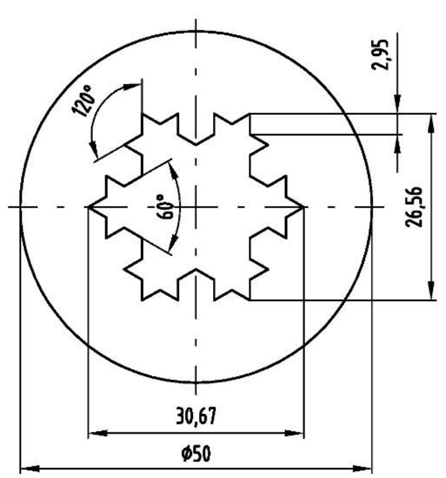

Figure 2. Dimensions of von Koch snowflake orifice

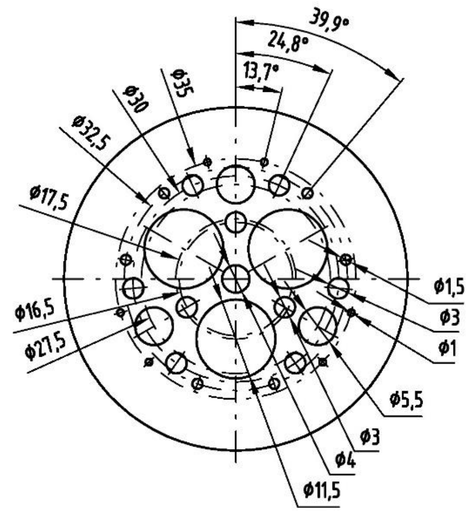

Figure 3. Dimensions of Apollonian gasket orifice

Figure 4. Dimensions of Apollonian gasket orifice

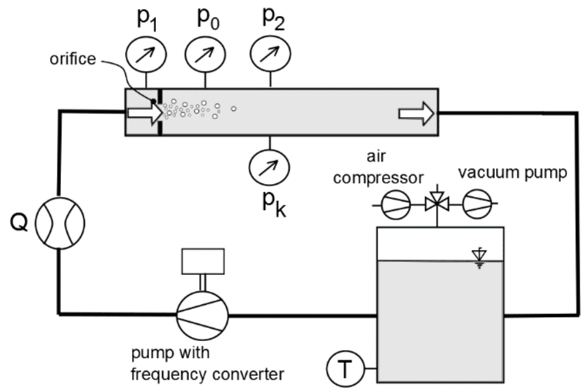

Figure 5. Scheme of the hydraulic circuit

Experiment

An experimental circuit was set up according to figure 5. Flow measured using induction flow meter, pressures were recorded in three positions, just ahead of the orifice and 150 mm (3 pipe diameters) and 500 mm (10 pipe diameters) downstream. Pressure sensors p_0 to p_2 were of tensometric type (DMP331, BD Sensors), sensor p_k is of piezoelectric type (Kistler).Pressure loss coefficient ζ and cavitation number σ were determined from pressure sensors p_1 and p_2. Vapor pressure p_{vapor} was computed from Clasius-Clapeyron equation as function of temperature. Velocity is define by bulk velocity in the orifice constriction.

$$\zeta = \frac{p_1 - p_2}{\rho \frac{v^2}{2}} \tag{1}$$

$$\sigma = \frac{p_2 - p_{vapor}}{\rho \frac{v^2}{2}} \tag{2}$$

Results in form pressure loss coefficient curves for both non-cavitating and cavitating regimes are plotted in figure 6. Curves in figure 6 also depict that cavitation inception for von Koch orifice is postponed compared to two other orifices. Loss reduction in non-cavitating regime for Apollonian gasket orifice is almost 25%. It is interesting to note that loss curve for Apollonian gasket orifice sticks to one-hole orifice curve with increasing intensity of cavitation. Pressure loss reduction is higher than measurement uncertainty.

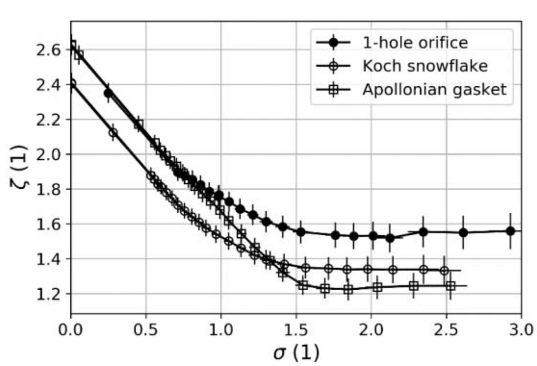

Figure 6. Loss coefficient curves

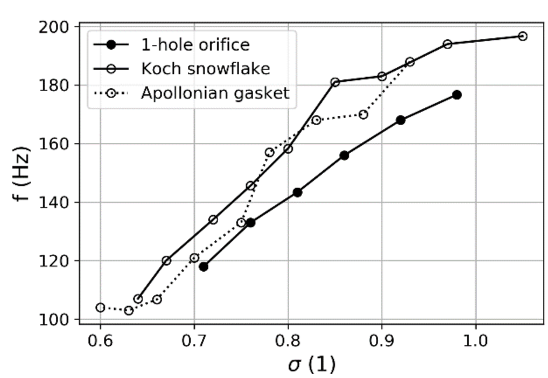

Figure 7. Frequencies of the dominant pressure peaks

Amplitude frequency spectra for cavitating regime were evaluated from wall pressures measured by piezoelectric sensor p_k. The frequency values corresponding to dominant peaks are plotted in figure 7. It is seen that those peaks are shifted from 10 to 20 Hz higher for fractal-shaped orifices compared to one-hole orifice. Pressure amplitudes are significantly higher for one-hole orifice as can be seen from comparison with von Koch snowflake orifice for cavitation number $\sigma = 0.72$, see figures 8, 9.

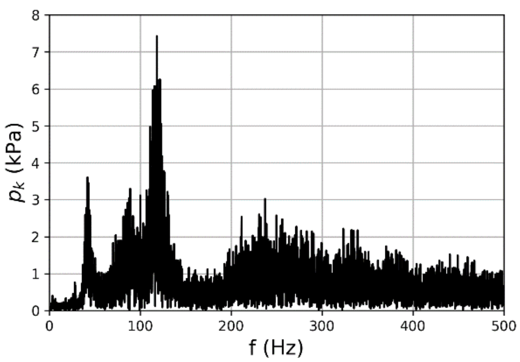

Figure 8. Amplitude frequency spectrum for one-hole orifice

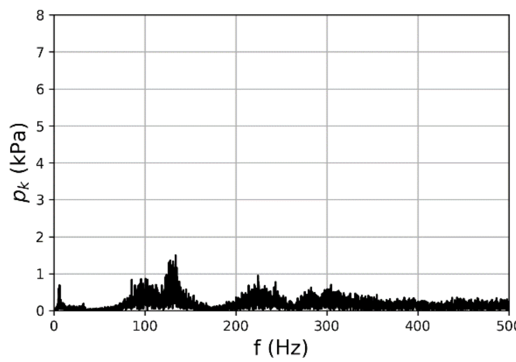

Figure 9. Amplitude frequency spectrum for von Koch snowflake orifice

Different behavior of the orifices is best seen for the supercavitation regime (figure 10). Well pronounced jet appears for one-hole orifice, while for both fractal-shaped orifices the jet is spread over the cross-section. For von Koch snowflake the spreading occurs just behind the orifice, for Apollonian gasket a bit further downstream.

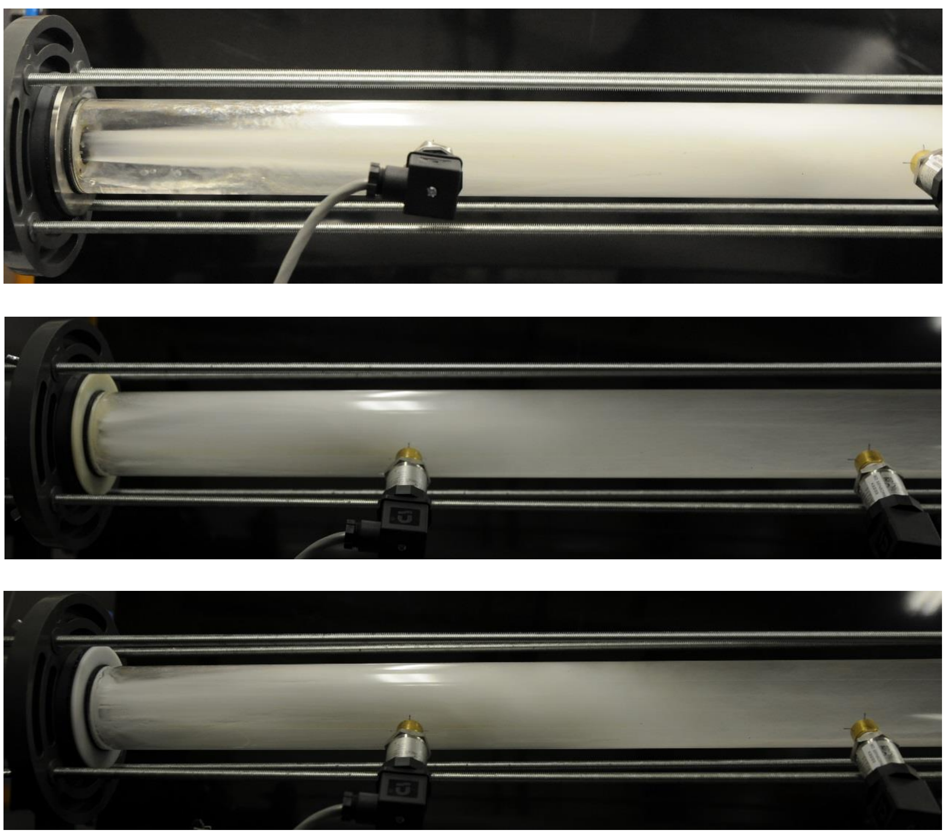

Figure 10. Supercavitation regime visualization (from top: one-hole orifice, von Koch snowflake, Apollonian gasket)

Conclusion

Experimental research of three orifice types with same cross-sectional flow area was carried out: one-hole, von Koch snowflake, Apollonian gasket. Following conclusions can be drawn:

- fractal shaped orifices reduce pressure in the non-cavitating regime compared to one-hole orifice of the same cross-section. The reduction is more significant for Apollonian gasket shaped orifice.
- when cavitation occurs von Koch snowflake orifice maintains the reduced pressure loss, compared to one-hole orifice, over whole operating range from initial cavitation to supercavitation
- frequencies associated with the most dominant peak in pressure spectrum are higher for both fractal shaped orifices compared to one-hole orifice
- amplitudes of wall pressures within the cavitating regime are substantially higher for one-hole orifice than for fractal-shaped orifices. Consequently level of noise (especially in von Koch orifice) is lower for fractal-shaped orifices.

All conclusions are connected with flow pattern generated by the respective orifice plates. One-hole orifice induces a strong vertical structure (vortex ring) associated with the length scale of the hole, i.e. its diameter. On the other hand fractal shaped orifices generate vortices on a whole range of scales, energy is distributed over a range length scales. Fractal shaped orifices might be used as flow constriction devices in situations, where low operating noise is required. Fractal shapes might also be used in control valves or polyjet sleeve valves [11] to achieve lower noise and faster decay of the kinetic energy. Application for fast, yet simple, mixing (combustion, chemical processes) is apparent.

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