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On cavitation occurrence in perforated plates

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A B S T R A C T

The hydraulics of perforated plates has a large impact on the design of water systems; particularly, estimating the inception of cavitation is fundamental for correctly assessing the performances of these devices. The work is focused on the onset of cavitation, as defined by means of the incipient cavitation number. Objects of discussion are the experimental evidences collected in two large laboratory campaigns, in which different plates with equivalent diameter ratio between 0.17 and 0.60, relative thickness between 0.11 and 4.40, and number of holes between 1 and 15 were tested. Literature experimental data, previously checked for consistency, have been added to ours in order to enlarge the experimental database. Such database was firstly employed for investigating the dependence of the incipient cavitation number upon the most relevant parameters and then for providing a formula for its estimation. In details, we propose a new correlation – based on the formula of Tullis (1993) – relating the incipient cavitation number to the discharge coefficient showing a satisfactory agreement with all the available data and therefore having a quite large applicability.

1. Introduction

Perforated plates are normally used within pressurized systems, as control or maintenance devices. Generally, these devices are installed upstream flowmeters for removing swirl and correcting a distorted flow profile or, coupled with a control valve, for preventing cavitation phenomena, assuring safe operating conditions [1,2].

Studies about the hydraulics of perforated plates are rather abundant; some of them aim at investigating the functionality of these devices as flow conditioners [3–7], being focused on their use for pre-conditioning a disturbed flow, whereas others mainly concern the analysis on the dissipation characteristics of perforated plates [8–18]. On the contrary, studies on the cavitation behavior of perforated plates are relatively few, despite the topic is engineering relevant. Most of the investigations concerning cavitation phenomena consider single hole plates [1,2,19–32], whilst the multi-hole case was addressed very rarely [33–35]. At present, the most comprehensive investigations about this topic seem those from Maynes and his co-workers [15,18], who analyzed the effect of the plate geometry on its cavitation characteristics; this research was anticipated by a preliminary work of one of the authors of the present article [36]. The present work fits into this context and aims at carrying forward the above-mentioned investigations, particularly providing further information related to cavitation inception in differently shaped perforated plates.

Cavitation can be roughly considered as the rapid vaporization and condensation of a liquid, caused by a sudden pressure reduction [37]. According to the ISA standard [38], different cavitation regimes can be identified measuring the indirect effects induced by cavitation phenomena in a hydraulic system, as the vibration: 1) REGIME I: absence of cavitation; 2) REGIME II: incipient cavitation, namely the onset of cavitation, where only small vapor bubbles are formed in the flow stream. This condition is detected when an abrupt increase in induced vibration level occurs after the collapse of the bubbles and the condensation of the vapor; 3) REGIME III: constant cavitation, involving a sufficiently large volume of vapor to produce a uniform and constant level of cavitation; 4) REGIME IV: maximum vibration, that is, the level of cavitation associated with occurrence of choking condition. The level of cavitation causing damages to a device is hard to define and is usually indicated on the basis of experience. Clearly the more conservative choice consists of restricting all operations to a cavitation-free regime even if typically the incipient cavitation level (REGIME II) may be acceptable in the design phase [1,38].

Cavitation is usually studied by means of the cavitation number for which several definitions exist. Hereafter, the following cavitation parameter definition, as proposed by the ISA standard [38], will be used:

$$\sigma = \frac{P_1 - P_V}{P_1 - P_2} \qquad (1)$$

where P_1 and P_2 are the pressures measured sufficiently far upstream and downstream the device (Fig. 1), in order to provide

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Nomenclature

A'	Acceleration (ms^{-2})
c'	Parameter in Eq. (8) (-)
C_c	Contraction coefficient (-)
C_d	Discharge coefficient (-)
d_h	Diameter of the holes (m)
D	Pipe diameter (m)
D_{ref}	Reference pipe diameter (m)
Eu	Euler number (-)
n_h	Number of holes (-)
P_1	Pressure at upstream reference section (Pa)
P_2	Pressure at downstream reference section (Pa)
P_V	Vapor pressure (Pa)
Re_h	Hole Reynolds number (-)
SSE	Size Scale Effects correction factor (-)
t	Plate thickness (m)
$u(\zeta)$	Absolute uncertainty on variable ζ
V	Pipe bulk-mean velocity (ms^{-1})
V_h	Average fluid velocity within the holes (ms^{-1})
Y	Parameter in Eq. (12) (-)
β	Equivalent diameter ratio (-)
$\varepsilon(\zeta)$	Relative uncertainty on variable ζ(-)
ν	Kinematic viscosity coefficient of the fluid (m^2s^{-1})
ρ	Fluid density (kgm^{-3})
σ	Cavitation number (-)
σ_2	Alternative definition of the cavitation number (-)
σ_c	Constant cavitation number (-)
σ_i	Incipient cavitation number (-)
σ_{mv}	Maximum vibration cavitation number (-)
σ_V	Alternative definition of the cavitation number (-)
MH	Multi-hole orifice
SH	Single-hole orifice

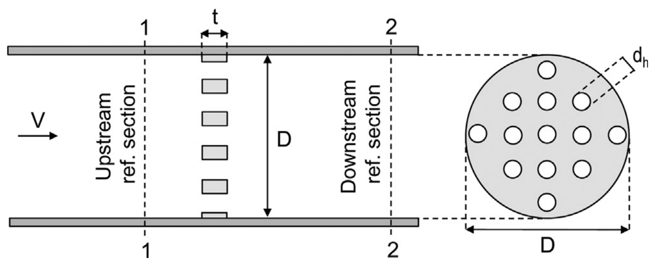

Fig. 1. Test longitudinal section: pressure measuring points.

reliable values of the gross pressure drop, and P_V is the vapor pressure. Similar definitions of the cavitation number, related to the above mentioned ones, are:

$$\sigma_2 = \frac{P_2 - P_V}{P_1 - P_2} = \sigma - 1 \quad (2)$$

$$\sigma_V = \frac{P_1 - P_V}{1/2\rho V^2} = Eu \cdot \sigma \quad (3)$$

where ρ is the fluid density, V is the pipe bulk-mean velocity (Fig. 1), and

$$Eu = \frac{P_1 - P_2}{1/2\rho V^2} \quad (4)$$

is the Euler number.

Different threshold values of σ are defined: the incipient cavitation number σ_i, where Regime II starts; the constant cavitation number σ_c, where Regime II meets Regime III; and the maximum vibration cavitation number σ_{mv} where Regime III ends. The incipient cavitation number σ_i identifies the first detectable onset of cavitation and, according to the ISA standard [38], it can be experimentally estimated in a semi-log plot of acceleration or sound pressure level measurements versus the cavitation index σ, where a first sudden increase of the data trend occurs (Fig. 2). It's worth emphasizing the difficulties inherent in this graphical procedure, which make it difficult to accurately estimate σ_i.

The incipient cavitation number is likely to be affected by the geometrical characteristics of the devices, expressed by the following parameters: (1) the porosity of the screen, that is, the ratio of the open area to the overall pipe section, usually expressed using the equivalent diameter ratio β; (2) the plate thickness t, usually taken into account by means of the dimensionless relative thickness t/d_h, d_h being the hole diameter; (3) the number of holes n_h; (4) the

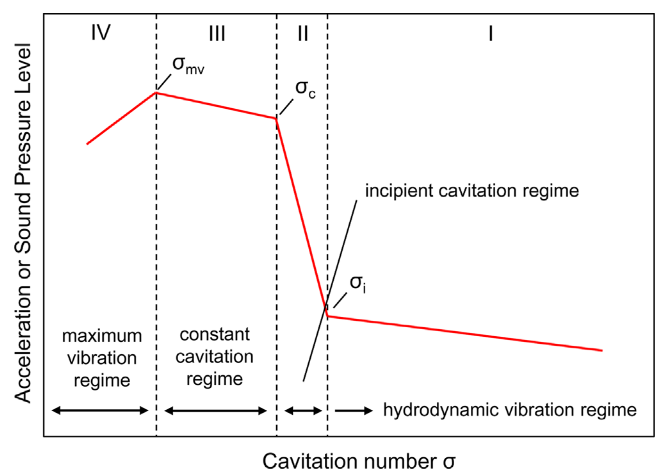

Fig. 2. Identification of the cavitation regimes and limits according to the ISA standard [38].

distribution of the holes and their shape, as well as the chamfering of their edges. In this article only devices having circular holes of uniform size, with a negligible radius of curvature at the edges of the holes, are considered. Although its influence is not analyzed in the present work, we underline that the shape of the holes is a key factor since the chamfering of the edges may result in a significant variation of the incipient cavitation number.

Holt et al. [15] found that the incipient cavitation number of perforated plates increases with β for $0.32 \le \beta \le 0.66$, meaning that cavitation inception is more likely to occur in plates with higher porosity. This result confirmed the outcomes of different researches regarding the single-hole case [1,2,20,21,23]. Nevertheless the effect of the relative thickness t/d_h on σ_i does not appear completely clarified yet. Maynes et al. [18] found that the trend of σ_i as a function of t/d_h is increasing until $t/d_h \approx 1$, and decreasing for longer orifices. The authors related this behavior to the transition within the holes between separated and reattached flows. Indeed, the dependence of σ_i upon n_h, the other parameters being the same, has never been systematically studied, as well as the influence of the shape, distribution, and chamfering of the holes.

Different approaches can be used for estimating the incipient cavitation number of perforated plates. In particular, two physically based models have been proposed by Nurick [24] and Sanchez et al.