Experimental Thermal and Fluid Science 53 (2014) 40–48

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Performance and image analysis of a cavitating process in a small type venturi

A.M. Abdulaziz *

Department of Mechanical Power Engineering, Faculty of Engineering, Ain Shams University, Cairo, Egypt

ARTICLE INFO

Article history:
Received 13 May 2013
Received in revised form 6 October 2013
Accepted 30 October 2013
Available online 15 November 2013

Keywords:
Cavitating venturi
Image processing
Vapor void fraction

ABSTRACT

A cavitating venturi is a flow control device usually used to deliver constant mass flow rate when operated at cavitation conditions. Experiments were conducted on a small type venturi test rig under varying upstream, throat and downstream conditions. A model for water vapor void fraction is proposed and validated against detailed image analysis of the cavitating process. Both experimental and model results showed that cavitation occurs at a certain critical pressure ratio (downstream pressure/upstream pressure) where the liquid starts to evaporate at the throat of the venturi. As the venturi pressure ratio is decreased than the critical pressure ratio, the mass flow rate is choked resulting in an increased vapor formation in the divergent part of the venturi. This can be predicted by the proposed model as well as the image analysis. Through all the conducted venturi experiments, the critical pressure ratio ranges from 0.70–0.72 corresponding to an upstream temperature of 21 °C. At a temperature of 42 °C the critical pressure ratio was increased to 0.75. Image analysis clearly shows the vapor formation from the throat up to the middle of the divergent part of the venturi. Traces of vapor are observed at the exit of the venturi where the thermodynamic conditions cannot maintain the existence of vapor bubbles.

1. Introduction

Experimental and theoretical studies were carried out to investigate the flow process through cavitating venturis.

The mass flow rate through a cavitating venturi is well correlated with the ratio of downstream pressure to upstream pressure. For this ratio of less than 0.8, the mass flow rate was constant and independent of the downstream pressure [1,2]. By applying a discharge coefficient and using only upstream pressure, the cavitating venturi can be used as a flow meter with a high degree of accuracy in a wide range of mass flow rate [1].

Liou and Chen [3] indicated that if the pressure ratio of downstream to upstream is more than 0.8, unchoking and overflow phenomena will be observed in the venturi.

Cavitation and phase change of water is modeled numerically using a homogeneous flow model and CFD techniques for venturis with different sizes of throat diameter ranging from 2.5 to 5.3 mm [4].

For the purpose of flow control in liquid rocket engines, Ulas [5] kept the upstream pressure constant by two methods and used an 11 mm cavitating venturi to provide a constant mass flow rate, independent of the downstream pressure.

Using a high speed camera, Sato et al. [6] concluded that cavitation aspects and the bubble occurrence count rate change with cavitation number (defined by Eq. (12) in the text) and water quality (dissolved gas content). For higher cavitation number, the occurrence positions tend to be around the wall surface while for lower cavitation number the positions tend to be distributed throughout the cross section of venturi throat.

Analysis of cavitating flows, through double optical probe measurements were performed to estimate the vapor void fraction and velocity fields for cold water flow in a venturi [7].

Fields of pressure, velocity and void fraction of cavitating process inside venturis are predicted numerically using various CFD models [8,9].

2. Objectives of the present work

The previous survey confirms that the cavitating venturi is a precise tool for controlling mass flow rate. However, more details are required to clarify the process of vapor formation in the divergent part of the venturi. The present work proposes an approximate model for vapor void fraction and its dependence on the venturi pressure ratio. The model is experimentally validated through image analysis of the cavitation process. Furthermore, the vapor distribution, formation and collapse are detailed.

* Tel.: +20 1227912259.
E-mail address: abdelaziz_morgan@eng.asu.edu.eg

0894-1777/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.expthermflusci.2013.10.010

Nomenclature

b	offset constant
C_d	coefficient of discharge
C_p	pressure recovery coefficient
C_{pm}	modified pressure recovery coefficient
D	diameter, m
i	axial point on the horizontal venturi axis
I	digitized light intensity, (0–255)
j	vertical point on the vertical venturi axis
L	length of the divergent part of venturi, m
k	constant
$\dot{m}$	mass flow rate, kg/s
P	pressure, Pascal
r	reflected light
Re	Reynolds number
V	velocity, m/s
x	axial distance from throat, m

Greek symbols

α	void fraction
γ	photoelectric conversion exponent
Θ	view angle
μ	viscosity, kg/m/s
ρ	density, kg/m^3
σ	cavitation number

Subscripts

ac	actual
d	downstream
th	throat
u	upstream
L	liquid
m	mixture
v	vapor

3. Theoretical background

The first part of this section presents the necessary equations for the proposed mathematical model of vapor formation inside the divergent part of a venturi. The second part describes the image analysis scheme used to verify the proposed model.

3.1. Model of vapor formation through a cavitating venturi

The governing equations of mass flow rate and vapor void fraction associated with the flow process through a venturi are derived in the next subsections.

3.1.1. Mass flow rate through a venturi

To develop an equation for the mass flow rate through a cavitating venturi, the flow process in the convergent part is assumed to be one dimensional isentropic flow. Also the density is assumed to be constant and equal to the liquid density at the operating temperature. Applying Bernoulli's equation between the inlet and throat of the venturi along the center streamline gives:

$$\frac{p_u}{\rho_L} + \frac{V_u^2}{2} = \frac{p_{th}}{\rho_L} + \frac{V_{th}^2}{2} \quad (1)$$

where p_u is the upstream pressure, p_{th} is the throat pressure, V_u is the upstream velocity, V_{th} is the throat velocity and ρ_L is the liquid density.

Substituting V_{th} from Eq. (1) into the continuity equation gives the mass flow rate:

$$\dot{m}_{ac} = \frac{C_d \frac{\pi}{4} d_{th}^2}{\sqrt{1 - \left(\frac{d_{th}}{d_u}\right)^4}} \sqrt{2\rho_L(p_u - p_{th})} \quad (2)$$

where $\dot{m}_{ac}$ is the actual mass flow rate; d_u and d_{th} are upstream and downstream diameters; C_d is the discharge coefficient. Although the back pressure at the end of the divergent part of the venturi does not appear in Eq. (2), it affects the mass flow rate during the non-cavitating flow process. As the back pressure decreases below the upstream pressure (consequently the throat pressure), the flow rate increases. This continues up to a certain value of the back pressure where the throat pressure approaches the saturation state corresponding to the liquid temperature. At this condition, a fraction of the liquid is converted to vapor at the throat causing the mass flow rate to be choked. Any further decrease in the back pressure will not affect the throat pressure and consequently, according to Eq. (2), the mass flow rate will not change. In order to correctly design a cavitating venturi, operating at a certain range of flow rates, the throat diameter is carefully selected to ensure saturation pressure at the throat corresponding to the liquid temperature.

3.1.2. Vapor formation versus venturi pressure ratio

The following analysis is based on the pressure recovery approach which has been developed for flow through diffusers. This approach was extended to account for non-recoverable head loss in venturis [10]. Adapted experimental results correlated the pressure recovery coefficient, C_p, with the following parameters [10–12]:

$$C_p = f\left(Re, \left(\frac{D_{th}}{D_d}\right), \text{cone angle}\right)$$

The pressure recovery coefficient in the divergent part of the venturi can be generally calculated as follows:

$$C_p = \frac{\int_{th}^{d} \frac{dp}{\rho}}{1/2 V_{th}^2}$$

Using the average mixture density, ρ_m, to approximate the integration, gives:

$$C_p = \frac{p_d - p_{th}}{1/2 \rho_m V_{th}^2} \quad (3)$$

Substituting the throat velocity V_{th}, calculated from the actual mass flow rate of Eq. (2), into Eq. (3) gives:

$$\frac{\rho_m}{\rho_L} = \frac{\left(1 - \left(\frac{D_{th}}{D_u}\right)^4\right)}{C_d^2 C_p} \frac{(p_d - p_{th})}{(p_u - p_{th})} \quad (4)$$

Using the substitution $c_{pm} = \frac{C_p \times C_d^2}{1 - \left(\frac{D_{th}}{D_u}\right)^4}$, then:

$$\frac{\rho_m}{\rho_L} = \frac{1}{C_{pm}} \frac{(p_d - p_{th})}{(p_u - p_{th})} \quad (5)$$

where ρ_m is the average mixture density through the divergent part of the venturi, ρ_L is the liquid density in the convergent part and C_{pm} is the modified pressure recovery coefficient.

As long as p_{th} is greater than the saturation pressure, the right hand side of Eq. (5) is equal to unity and the average mixture density is equal to the liquid density. Once the throat pressure reaches the saturation condition, the flow is choked and the coefficient of