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DESIGN, TEST AND VALIDATION OF CAVITATING VENTURI ELEMENT USING IN LPRE

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ABSTRACT:

Cavitating venturis mainly use in liquid rocket propulsion to obtain constant mass flowrate, independent of downstream pressure changes.
The mass flowrate through cavitating venturi is function of upstream pressure, throat area of venturi, liquid density, vapour pressure of liquid, discharge coefficient of the venturi and downstream to upstream pressure ratio. A 1-D modelling study for mass flowrate through cavitating venturis has been conducted by means of Ecosimpro. Additionally, in order to validate Ecosimpro models, two experimental test setups with water supply system have been established. Four cavitating venturis having different throat areas have been designed, manufactured and tested for validation.
As a result, Ecosimpro cavitating venturi flow model shows good agreement with the experimental study. Developed Ecosimpro cavitating venturi model can be used to analyse different liquid flows through the venturis that have different throat diameter.

1. INTRODUCTION

Providing necessary oxidizer and fuel flow rates during the operation of Liquid Propellant Rocket Engine (LPRE) is an important topic for a stable operation. The methods which are used for this purpose divide into active and passive flow control systems.
Although active flow control systems consist of electrically operated valves, flowmeters, control units etc., passive flow control systems do not mainly depend on complicated hardwares such as computers, electrically operated systems.
Due to tight weight restrictions, passive flow control systems would be more favourable than active ones. Cavitating venturis, a passive flow control device, has been utilized in many liquid propulsion systems such as Lunar Module Descent Engine, RL-10 Engine, etc. [1, 2].
Cavitating venturi consists of converging and diverging sections. According to Bernoulli's Law, as a liquid flows through the converging section of the venturi, its velocity increases. Thus, static pressure of the liquid decreases down to saturation (vapour) pressure. At this moment, cavitation begins to occur at the throat of the venturi and a mixture of vapour and liquid forms as bubbly flow in throat region [3]. While the downstream pressure remains below 0.7-0.8 of upstream pressure, cavitation does not break and the flow velocity at the throat is equal to speed of sound of fluid-vapor mixture and flow inside the venturi becomes choked, in other words, flowrate does not change. Main advantage of this phenomena is that as long as the inlet pressure of cavitating venturi remains constant, stable flowrates can be obtained without affected rocket engine combustion dynamics.
Cavitating venturis have two modes of operation, one is choked mode and the other one is all-liquid mode. At the first one, cavitation happens in the throat and the flow becomes chocked. Under such a condition, the mass flowrate becomes constant and independent from downstream pressure. At the same time, cavitation causes formation of a two-phase flow in the throat and diffuser section. The mass flowrate is calculated by using Eq.1:

$$\dot{m}_{choked} = C_d A_{th}\sqrt{2\rho\left(P_{in} - P_{vap}\right)} \qquad \text{Eq.1}$$

where C_d is discharge coefficient and A_{th} is the throat area of cavitating venturi.
The location where the vapour area terminates, i.e. liquid flow reattaches to the diffuser, is a function of the downstream pressure. As the downstream pressure increases, the reattachment point moves upstream towards throat. When the downstream pressure reaches a certain value such that reattachment point reaches the throat, no cavitation will occur. This is the situation where the all-liquid mode starts [3]. For this condition, Eq.1 is no longer valid for mass flowrate calculation. The change of liquefaction length with downstream static pressure for cavitating venturis is illustrated in Fig.1:

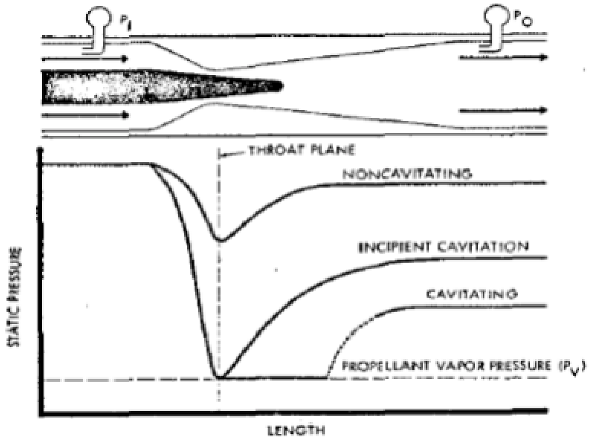


Figure 1 Typical Pressure Profile Through Cavitating Venturi [6]

2. DESIGN AND MODELLING

2.1. Design of Cavitating Venturi

Likewise the fact that flow control of compressible fluid is provided by using De Laval nozzle, it can be achieved by using cavitating venturi for incompressible fluids. Smallest area, which liquid can pass, is named as throat area. In this section, the static pressure of the flow must be lower than vapour pressure of liquid. As a result, a very rapid phase change transition from liquid to gas occurs in the flow [4]. There is a dramatic increase in the volume of the fluid, which constricts the flow, and a choked flow regime is obtained during this phase change [5].

As the Eq.1 states that throat area, inlet and outlet pressures of venturis and discharge coefficients are important parameters while designing a cavitating venturi. Moreover, the converging and diverging section angles must be selected such that minimum pressure losses can be provided.

Four cavitating venturis were designed, manufactured and tested for different mass flowrates by using water as the design fluid. High downstream pressure were chosen while designing as if there was a rocket engine. This results in to obtain given inlet pressure in Tab.1. In addition to that, inlet and outlet diameters were selected as equal to pipe diameters of related test setups. The discharge coefficient was taken as equal to 0.95 for initial design, although it should be determined experimentally. Moreover, the angles of converging and diverging sections were selected as 15° and 7° respectively so that minimum pressure losses can be obtained [5]. A detailed information of designed cavitating venturis are given in Tab.1:

Table 1 Designed Cavitating Venturis

Cavitating Venturi	Throat Diameter [mm]	Design Mass Flowrate [kg/s]	Inlet Pressure [Bar]	Inlet & Outlet Diameter [mm]
CV-1	1.7	0.147	23.5	10.92
CV-2	2.62	0.365	25.5	10.92
CV-3	13.44	8.98	22.3	44.96
CV-4	8.09	3.47	25.3	44.96

2.2. Modelling of Cavitating Venturi

To analyse and to observe cavitation behaviour of the designed venturis, an Ecosimpro model has created by using Fluidapro library. In this model a new component was created by using Pipe and Junction components. There are also input and output ports to connect this component to the others. The schematic of the created model is given in Fig. 2:

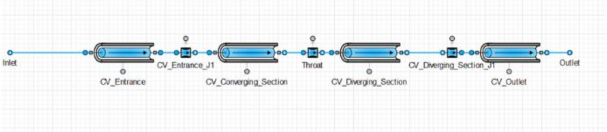


Figure 2 Schematic of Cavitating Venturi Model

The created Cavitating Venturi component requires initial pressure, initial temperature, pipe thickness, main pipe diameter, throat diameter, converging and diverging side angles, venturi's throat length and converging and diverging side profiles as inputs.

The developed model consists of 4 pipe and 3 junction elements. Although two pipe components, which are named as "CV_ Entrance" and "CV_Outlet", are just straight pipes, the others represent the contour of cavitating venturi with related angles. Those components have less nodes than "CV_Converging_Section" and "CV_Diverging_Section". Therefore, this enables to observe liquefaction point for flow. The model also gives permission to analyse any arbitrary profile for venturi. In addition to that, while analysing CV-1 and CV-2 the length of throat section is taken as 0.005 m, in spite of the default value 0.001 m. Having such an arrangement gives more related results with theoretically calculated values. Then, it was noticed that throat length in meters should be modified as in Eq. 2:

$$l_{modified} = \frac{D_{pipe}[mm]}{10.92} * 0.005 \qquad \text{Eq.2}$$

By implementing Eq. 2, CV-3 and CV-4 also give more reasonable results with theoretical and experimental values.

The component is analysed in another case. The schematic of the case is shown in Fig.3:

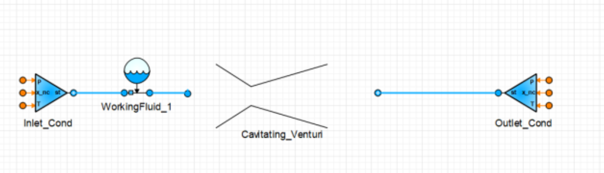


Figure 3 Schematic of Test Case

In this case, working fluid selected as water and inlet & outlet conditions are constructed as the same conditions with experiments.

3. EXPERIMENTS

3.1. Test Setups

Experiments were mainly conducted in two test setups which has related pipe sizes as given in Tab.1. Test setups were designed as representative branches of a pressure-fed liquid rocket engines. A gas pressure regulator and pneumatic actuating valves are used in order to provide necessary pressure for cavitating venturi. Both test setups are similar and a sample schematic of two test setups is shown in Fig.4:

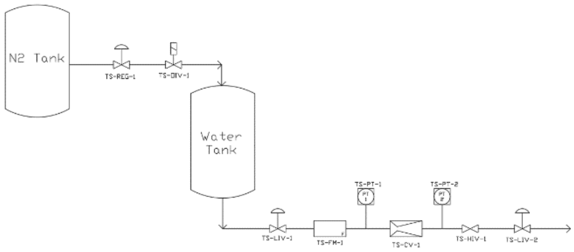
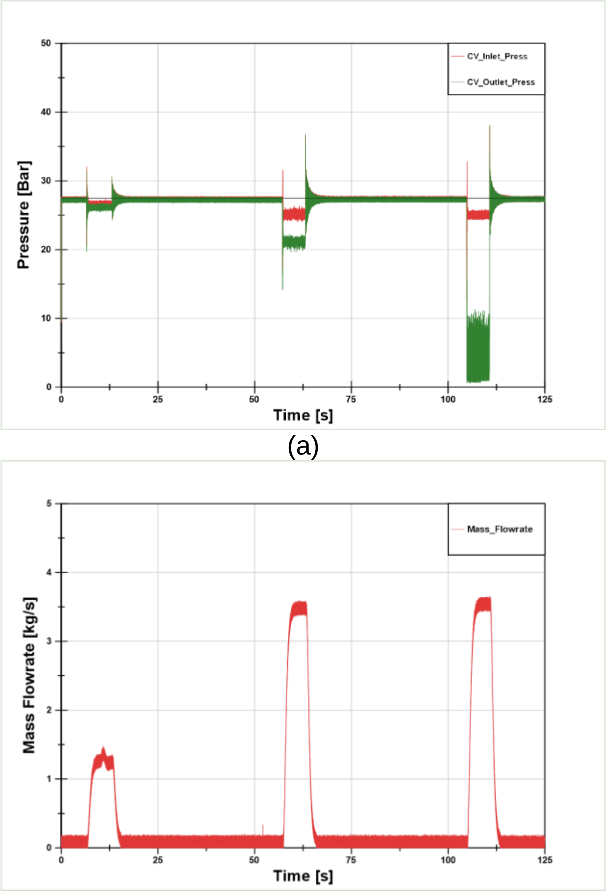


Figure 4 Sample Schematic of Test Setups

For each cavitating venturi, nitrogen was used as pressurizing gas and deionized water was used as test liquid. Firstly, high pressure tanks are opened in order to provide high pressure to the upstream side of the regulator and then regulator is set the necessary pressure to achieve the required inlet pressure for each test. Afterwards, tank is filled with deionized water. Then gas isolation valve (TS-GIV-1) is opened to pressurise tank. During the pressurisation, liquid isolation valve (TS-LIV-1) is opened to reach the test liquid to the upstream of second isolation valve (TS-LIV-2). There is also an additional hand valve, which is positioned after cavitating venturi, to obtain downstream pressure for each test. After pressurising is completed, LIV-2 becomes open and test starts. The pressure of the upstream and downstream side of venturi and the flowrates are recorded for each test.

A sample test result for CV-4 is given in Fig.5:



(a)

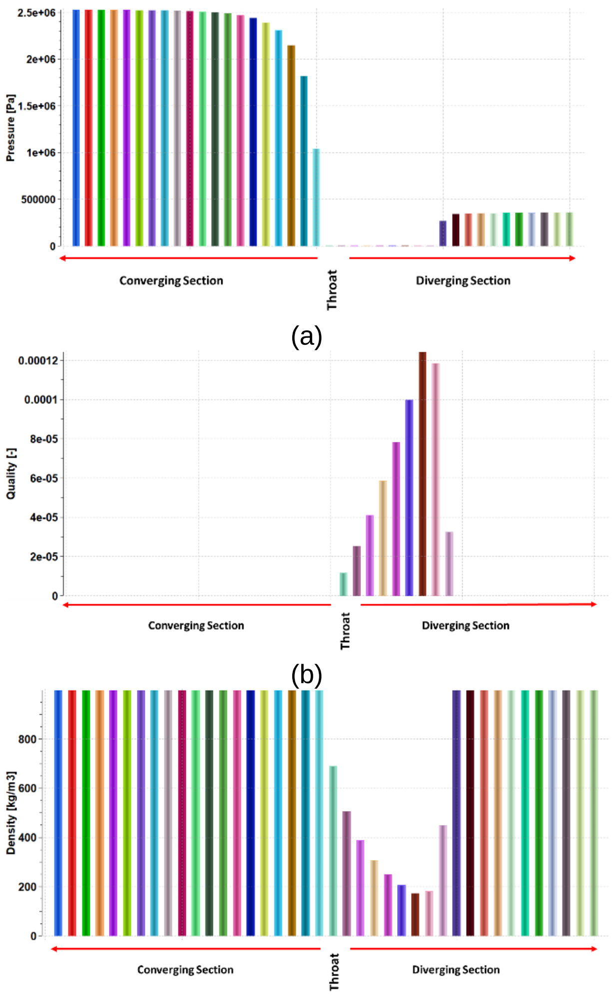
(b)

Figure 5 Test results for CV-4 (a) inlet&outlet pressures and (b) related flowrate for each test

As it can be seen from Fig.4, for the first test, downstream pressure is too high to get the design mass flowrate. Thus, it can be concluded that cavitating venturi is noncavitating and operates in all-liquid mode. For the second test, mass flowrate is obtained and downstream pressure is enough for cavitation. The result also shows liquefaction of flow was completed at a point between pressure sensor and venture throat. This case may be related to incipient cavitation giving in Fig.1. Third test expresses how cavitating venturi flow behaves when the downstream pressure is low. Oscillating behaviour, because of bubbly flow, of cavitation can be seen from the outlet pressure. This shows liquefaction of the flow had not completed at the position of outlet pressure transducer.

4. RESULTS and CONCLUSION

A simple test case is run in EcosimPro with the configuration of Fig.3. A steady state pressure, quality and density profiles and flowrate versus time graph has drawn for each venturi model. As an example, all output graphs are presented in Fig.6 for the final test condition of CV-4 which has 25.3 Bar inlet pressure condition and 3.54 Bar outlet pressure condition, respectively.



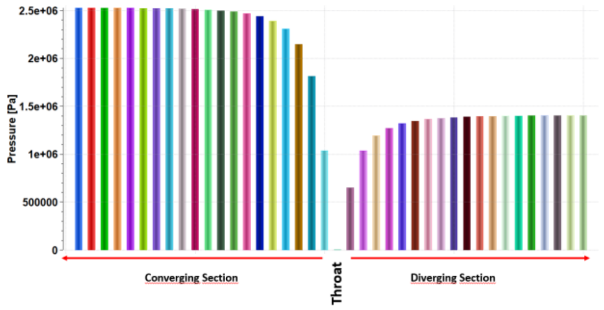
(a)

(b)

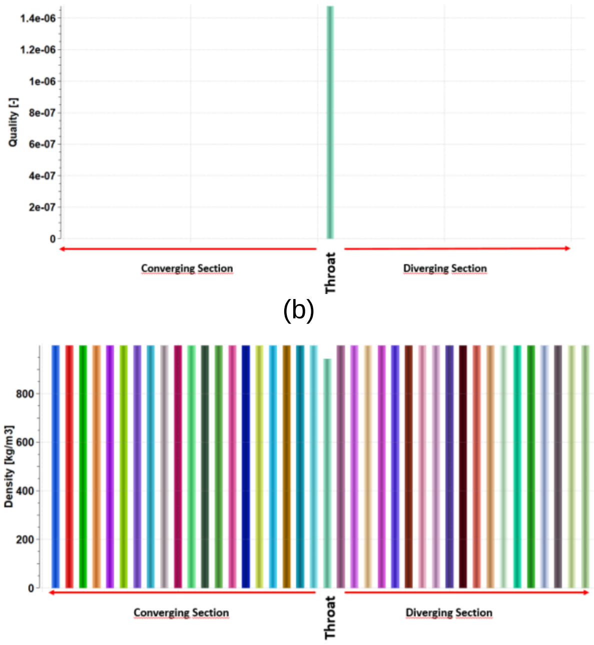
(c)

Figure 6 Analysis results of the test condition for CV-4 (a) Pressure Profile, (b) Quality Profile, (c) Density Profile

As it can be seen from Fig.6 the liquefaction of the flow completes in diverging section for 3.54 Bar downstream pressure. Furthermore, obtained mass flowrate is almost the same as what was obtained from the experiment. If downstream pressure increases, liquefaction point closes to throat and at some point it increases pressure in throat section. Fig. 7 shows the same graphs as Fig. 6 but for downstream pressure of 14 Bar.



(a)



(b)

(c)

Figure 7 Analysis Results of 14 Bar Downstream Pressure Condition for CV-4 (a) Pressure Profile, (b) Quality Profile, (c) Density Profile

After that point (14 Bar), the throat pressure is getting increased as downstream pressure increases, although there is a very small change in mass flowrate. Mass flowrate should not change up to 20 Bar downstream pressure according to test results.

Mass flowrate and required downstream pressure for breaking cavitation results obtained from experiments and analysis are presented in Tab 2 and Tab 3, respectively.

Table 2 Mass Flowrate Results

Venturi	**Design Mass Flowrate [kg/s]**	**Experiment Mass Flowrate [kg/s]**	**Model Mass Flowrate [kg/s]**
CV-1	0.15	0.14	0.15
CV-2	0.37	0.36	0.36
CV-3	8.98	8.94	9.04
CV-4	3.47	3.47	3.51

As it can be figured out from Table 2, there is a very good aggrement (±%5) among the design, experiment and model mass flowrate results.

Table 3 Cavitation Break Point Results

Venturi	Design Cavitation Break Pressure [Bar]	Experiment Cavitation Break Pressure [Bar]	Model Cavitation Break Pressure [Bar]
CV-1	18.8	17.9	17
CV-2	20.4	21.3	18
CV-3	17.8	19	17
CV-4	20.2	21.5	18

It is concluded that although the constructed model has very good agreement with mass flowrate results, it still needs a further development to perform exact cavitation behaviour.

5. REFERENCES

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