IAC-15-C4.3.1

JET INDUCER FOR A TURBO PUMP OF A LIQUID ROCKET ENGINE

Martin Böhle
Technical University Kaiserslautern, Germany, martin.boehle@mv.uni-kl.de

Wolfgang Kitsche
German Aerospace Center (DLR), Germany, wolfgang.kitsche@dlr.de

Samuel Sudhof
German Aerospace Center (DLR), Germany, samuel.sudhof@dlr.de

Liquid rocket propulsion systems are able to provide thrust at high specific impulse and at high thrust to weight ratios. One requirement to achieve this objective is a high combustion pressure which again requires a strong and efficient feed system. In large propulsion systems turbo pumps are used to obtain a high combustion pressure. In order to keep the mass of the pumps low the pumps are operated at very high rotational speed. Despite this a high suction performance without cavitation in the impeller is required. The state of the art designs use a so called inducer to guarantee good suction performance at high rotational speed. This publication proposes a non-rotating jet inducer which promises a higher performance and higher efficiency than the conventional inducer. The here proposed jet inducer completely replaces the conventional inducer. It works on the principle of the jet pump, a suction jet is injected before the inlet of the turbo pump and increases the total pressure of the fluid before it enters the impeller. The flow for the jet is taken from the pressure side of the pump itself and can be adjusted by a control valve depending on the operational point of the pump and on the operation phase (steady state or transient). The main component of the jet inducer is a set of aerodynamic profiles with nozzles at the trailing edge. The profiles have a star-like arrangement. The advantage of the jet inducer is the capability to increase the pressure without applying swirl on the fluid and hence promising a higher efficiency of the complete turbomachine. Due to the regulation of the jet flow we can also expect a higher suction performance of the impeller. In operational points where the tendency to cavitation increases (transient, low inlet pressure, over speed) we apply high mass flow on the jet inducer, in normal condition we reduce or stop the flow of the jet.

INTRODUCTION

One of the main objectives in launcher systems for space transportation is the request of a high payload factor. The structure and all sub-systems have to be minimised in mass related to the payload. For the propulsion system this turns out into a request of a high thrust to weight ratio (TW ratio) and a high specific impulse, I_{sp} (ratio of thrust to propellant flow). For ground to orbit transport the pump fed liquid rocket propulsion system provides the best TW ratio and I_{sp}. This is possible due to high combustion pressure and due to an oxidiser/fuel combination which provides high energy. The increase of combustion pressure is a continuous development in rocket propulsion technology. The DLR operates a test facility dedicated to thrust chamber development with interface pressure (test facility / test chamber) up to 300 bar.

The decisive components for high pressure are the fuel- and the oxidiser-pump. A small pressurisation is already applied on the propellant tanks by gas pressurisation. One reason for this pre-pressurisation is the request of a sufficient net-pressure-suction-head, NPSH at the pump inlet. Especially for cryogenic propellants the effect of cavitation is likely and can be avoided by tank pressurisation. A pump with better suction performance (low required NPSH) has the benefit of lower tank pressure which directly saves structural mass of the tanks. Therefore the development target for the propellant pumps is not only a high pressure raise but also a good suction performance.

For liquid rocket engines normally turbo pumps with axial to radial flow are used. Another common design feature is a high rotational speed possible due to adequate materials (titanium e.g.) of the rotating parts. The suction performance is normally increased due to a so called inducer, a helix shaped rotating turbomachine component for mainly axial flow. It is resistant to cavitation at its intake and increases the total pressure toward the inducer outlet. In doing so the inducer turns the gas fraction in the fluid back to liquid state. The swirl of the fluid at the outlet of the inducer is normally reduced by guide vanes before the fluid enters the impeller. Compared to other pump components the efficiency of the inducer is poor respectively when we consider the loss in the subsequent guide vanes. These pump design features provide high pressure raise and good suction performance with mostly only one impeller wheel on one hand but at poor pump efficiency on the other hand. To increase the pump performance without further efficiency loss or even efficiency increase a new design concept is investigated here. The so called jet inducer promises better performance and better efficiency and on top of that it offers an additional possibility to regulate the pump.

NOMENCLATURE

Abbreviation	**Unit**	**Denotation**
DLR		German Aerospace Center
NSPH		Net Pressure Suction Head
LRE		Liquid Rocket Engine
TW ratio		Thrust to Weight Ratio
Symbol		
A	m^2	Area
e	J/kg	Specific Energy
$\dot{m}$	kg/s	Mass Flow
$\dot{V}$	m^3/s	Volume Flow
ρ	kg/m^3	Density
p	Pa	Pressure
c	m/s	Velocity
Δy	J/kg	Specific Work
α		Area Ratio
φ		Velocity Ratio
n	1/min	Rotational Speed
η		Efficiency
I_{sp}	m/s	Specific Impulse
Index		
A		Pump A
B		Pump B
JI		Jet Inducer
PI		Pump Inlet
II		Impeller Inlet
ref		Reference Point
crit		Value at Cavitation Onset
Vortex		Characteristic Vortex

LIQUID ROCKET ENGINES (LRE)

The available propulsion systems for ground to orbit launchers (fig.1) can be classified according their oxidiser/fuel types. Due to the high thrust the solid propellant is mostly used at sea level start, its better specific impulse, I_{sp} calls for the liquid rocket engine (LRE) for upper stage propulsion systems. A combination of both is the hybrid rocket engine, it applies one of the propellants in liquid (or gaseous) state and the other component in solid state. The LRE again can be classified in pump fed and pressure fed rocket engines, where the pump fed engine offers the higher combustion pressure. The pumps of the LRE are normally driven by turbines which are fed by a gas generator (gas generator cycle engine, fig.2), by a pre-burner or by a fluid which is increased in enthalpy in a heat jacket of the combustion chamber (expander cycle engine). The arrangement of pumps and turbines mostly depends on the fuel/oxidiser combination. Single or dual shaft configurations, use of a gear box and common or separate turbines for the pumps are possible configuration in LREs.

Figure 1 Ariane 5 Launcher

Courtesy of ESA

Figure 2 Vulcain 2, LRE

Courtesy of SNECMA

PROPELLANTS PUMPS

Among the various types of pumps the radial turbo pump is favourable for the propellant feed system of a liquid rocket engine. It consists of one or more rotating impeller(s), a diffusor with or without guide vanes, an outlet manifold and an inducer in front of the impeller. For LRE a simple, small and light pump is desired therefore the number of impellers is minimised to mostly one impeller (fig.3) while a good efficiency is set aside. To reach this objective the impeller tip speed of state-of-the-art pumps goes up to 700 m/s and more. A sufficient strength of the impeller can be obtained with titanium materials and an advanced impeller shape.

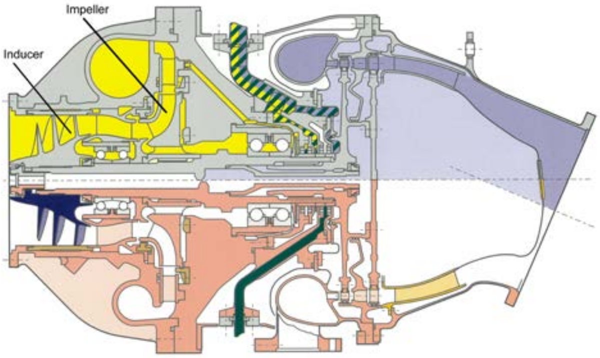

Figure 3 Vulcain 2, Oxygene Pump
Courtesy of SNECMA

The high impeller speed causes the risk of cavitation at the inlet of the impeller. Especially for cryogenic fluids, which are very interesting for liquid rocket engines, the cavitation limit is very close. To avoid cavitation in the impeller since sixty years the inducer, upstream the impeller was developed (fig.6). The task of the inducer is to increase the total pressure of the fluid in order to have a reasonable margin to the saturation line of the fluid when it enters the main impeller. The conventional inducer (fig.4) is a helix shaped rotating turbomachine component for mainly axial flow. It is resistant to cavitation at its intake (fig.5) and increases the total pressure toward the inducer outlet. In doing so the inducer turns the gas fraction in the fluid back to liquid state which also contributes to the total pressure raise of the pump. The swirl of the fluid at the outlet of the inducer is normally reduced by guide vanes before the fluid enters the impeller. Compared to other pump components the efficiency of the inducer is poor respectively when we consider the loss in the subsequent guide vanes.

Figure 4 Conventional Inducer
Source Technical University, Kaiserslautern

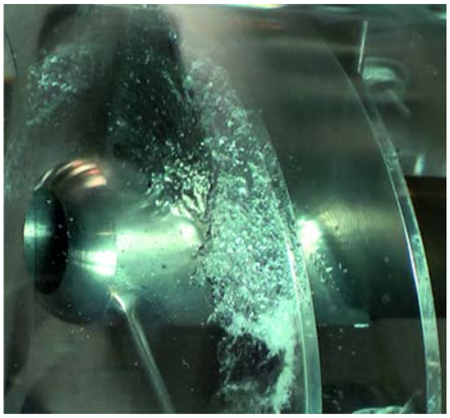

Figure 5 Cavitation at Inducer Inlet
Source Technical University, Kaiserslautern

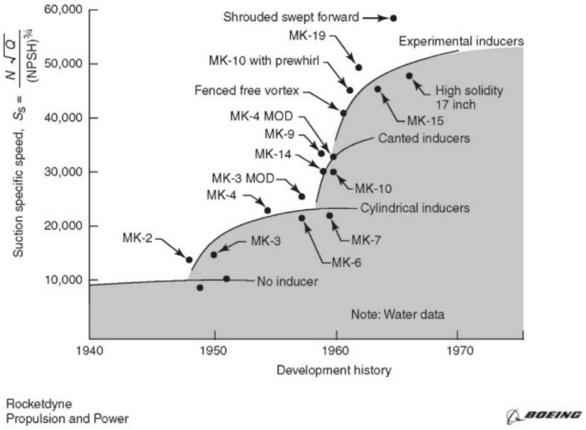

Figure 6 Inducer development
Source Rocketdyne

JET INDUCER

The application of a jet pump in a LRE was proposed by several authors. N. A. Brikner[1] investigated an injector pump in a micro rocket engine, D. L. Crabtree[2] investigated a gas-driven jet pump for rocket engines and A. Okayasu[3] et alia improved the pump suction performance of the Japanese LE-7A rocket engine by a jet pump and considers this feature as a key technology for reusable rocket engines.

The here proposed jet inducer completely replaces the conventional inducer of the turbo pump. It works on the principle of the jet pump and needs no rotation part. In a jet pump (fig.7) two flows of the same direction but of different velocity are mixed. The effect is an energy transfer from the flow of high velocity to the flow of smaller velocity and the result is a mixed flow where mass and energy conservation is applicable.

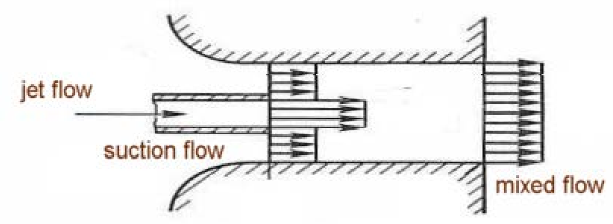

Figure 7 Principle Flow in a Jet Pump

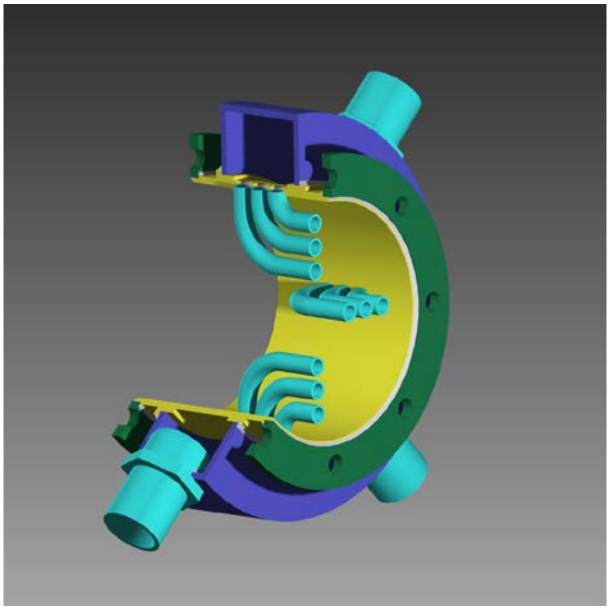

Figure 8 Jet Inducer with Supply Manifold (blue)

In the jet pump the suction effect is in the focus, in the jet inducer (fig.8) the energy and pressure raise of the flow is in the focus but the principle is the same.

The theoretical approach for the fluid process is derived from the perfect jet inducer (mass and energy conservation) and an additional loss model. Due to the fact that only one incompressible fluid is involved the mass balance is reduced to a balance of volume flow.

$$\dot V_{PI} + \dot V_{JI} = \dot V_{II} \qquad [1]$$

$$\left[\dot V\left(\tfrac{1}{2}\rho\, c^2 + p\right)\right]_{PI} + \left[\dot V\left(\tfrac{1}{2}\rho\, c^2 + p\right)\right]_{JI} = \left[\dot V\left(\tfrac{1}{2}\rho\, c^2 + p\right)\right]_{II} + L_{loss} \qquad [2]$$

The loss L_{loss} in the mixing process is calculated by the mass flow in the mixing area and by the specific rotation energy of a characteristic vortex.

$$L_{loss} = \dot m_{mix}\ e_{Vortex} \qquad [3]$$

The vortex energy again is calculated from the velocity difference between jet flow and suction flow.

The description of the performance of the jet inducer is given in terms of coefficients. The two most significant coefficients are the area ratio α and the velocity ratio φ .

$$\alpha = \frac{A_{J\,I}}{A_{I\,I}} \qquad \varphi = \frac{c_{P\,I}}{c_{J\,I}} \qquad [4]$$

(In this study the pump inlet area $A_{P\,I}$ is equal to the impeller inlet area $A_{I\,I}$)

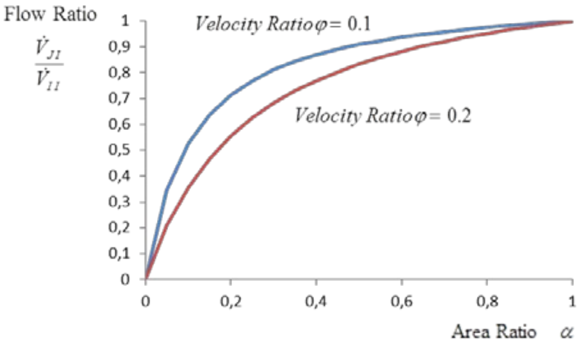

Figure 9 Flow Ratio in a Jet Pump

Our application of the jet inducer is to amplify the performance (suction and pressure raise) of the pump in a configuration where the jet inducer is in front of the pump impeller. The pressure side of the impeller (outlet manifold) is tapped for a backflow to drive the jet inducer (fig.10).

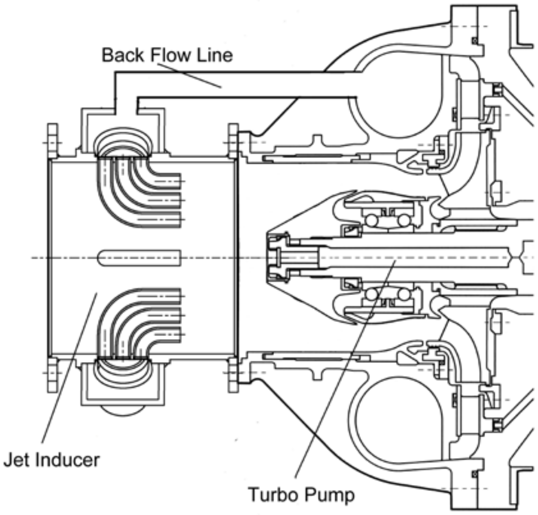

Figure 10 Jet Inducer in front of a Turbo Pump

It means that the backflow permanently circulates through the impeller, which increases the design size of the impeller. With respect to energy and pressure raise a part of the fluid passes the impeller again and again which means a far higher energy transfer from the impeller (or shaft) to the fluid due to the jet inducer.

To increase the impeller size is normally no problem for a turbomachine designer but the increase of the pressure raise is limited (by the max. tip speed e.g.). In other word, due to the jet inducer it is possible to increase the pressure raise by selecting a bigger impeller. This advantage of high pump pressure is very interesting but the even more interesting advantage of the jet inducer is the increase of suction performance.

The conventional inducer creates a low pressure zone at the suction side of its leading edge, at this point its suction performance is limited. The jet inducer creates no low pressure zone but a zone of higher pressure therefore its suction performance is in principle not limited.

The mixing process in the jet inducer is not perfect but the loss is likely less than the loss in a conventional inducer. The applied loss model confirms this but nevertheless it has to be demonstrated in experiments.

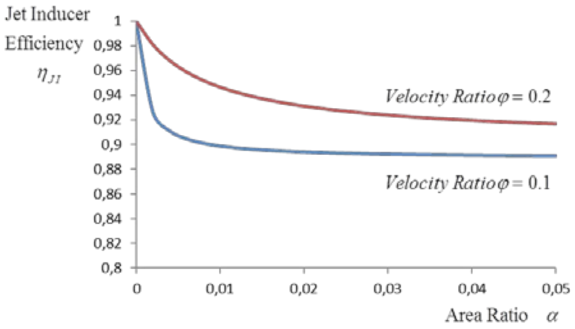

Figure 11 Efficiency of the Jet Inducer

Further advantages of the jet inducer are the facts that it is a non-rotating component and that it offers a tool for pump regulation, at constant rotational speed the mass flow and pressure can be adjusted and the pump can be kept at a short margin to its suction limit. Regulation includes the possibility of a complete shut-down of the inducer jet when the suction flow has enough pressure (NPSH). In the shut-down case the pump runs only on the main impeller and provides the best efficiency.

Advantage of the Pump with a jet Inducer

To illustrate the benefit of the jet inducer we compare a pump with one impeller, without inducer (pump A) to a pump with the same impeller, at the same rational speed but with a jet inducer (pump B).

For a (in terms of α , φ) defined jet inducer the ratio of the volume flow of the inducer and the pump inlet is also defined (fig.9). The velocity coefficient mainly depends on the pressure ratio between pump inlet and outlet. High pressure ratios require a throttling of the backflow to avoid an extreme velocity coefficient, which should not be less than 0.1 otherwise we would create too much loss (fig.11). Furthermore we want a low volume ratio which limits the selected φ and requires a very low area ratio α . The chosen jet inducer has an area ration α = 0.04 and a velocity ratio of φ = 0.1. Due to this jet inducer pump B has 35% more pressure raise while the flow is 29% less than in pump A. The jet inducer effects a shift of the pump characteristic to higher pressure and lower flow at the same speed (fig.12).

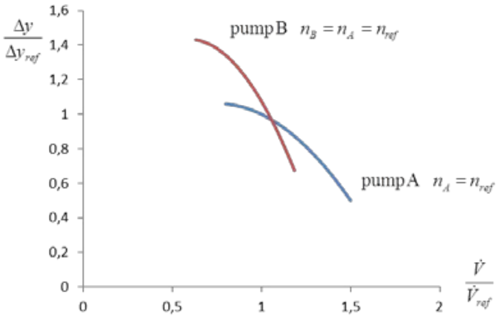

Figure 12 Shift of Pump Characteristic

If pump A was operated e.g. 10% above the critical net pressure suction head ($NPSH/NPSH_{crit} = 1.1$) the jet inducer increases this margin drastically and pump B runs at a ratio of $NPSH/NPSH_{crit} = 4.5$ (fig.13).

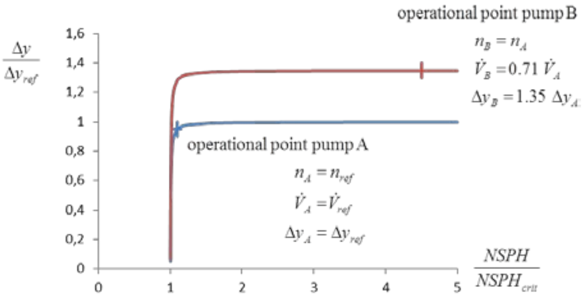

Figure 13 Increase of Cavitation Margin

CONCLUSION AND OUTLOOK

The fluid-mechanical function of the jet inducer and its interaction with a radial impeller is laid down in a consistent theory which sufficiently describes the principle behaviour of the jet inducer / impeller combination. A numerical scheme based on the jet inducer theory provides very interesting results of jet inducer application in turbo machines in rocket engines. The basic advantage of the jet inducer is its ability to provide an effective suppression of cavitation at the impeller inlet. The second advantage is the ability to increase the power of the pump with respect to the pressure raise. Another advantage is the possibility of regulation, the additional pressure raise and the cavitation-protection can be adapted according the operational point by simple flow control of the inducer jet.

The next step in the jet inducer project will be the design of a jet inducer for application in combination with a water pump and a test campaign to validate the principle behaviour and to investigate the interaction of the jet and suction flow. Further on a campaign to validate the performance forecast and to investigate the regulation and start-up behaviour is planned.

The validation of the jet inducer application in turbo pumps for rocket engines can be made by replacing the conventional inducer of an existing pump by a jet inducer (fig.10) and a dedicated test campaign to demonstrate the jet inducer performance in original fluids.

---

[1] Brikner, N. A. et alia, 2011, Investigation of heat Transfer and Scale Effects on the Performance of a Giffard Injector-Pumped Microrocket – Duke University, Durham

[2] Crabtree, D. L., 1962, Investigation of a Gas-Driven Jet Pump for Rocket Engines – Purdue University

[3] Okayasu, A. et alia, 2002, Key Technology for Reusable Rocket Engine Turbopump – Acta Astronautica, ELSEVIER