Injector Flow Characteristics

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## Injector Design and Chamber Conditions

In the process of designing a rocket engine, one of the most important factors determining the conditions within the combustion chamber is the injector design. The injector is the perforated plate separating a manifold of fuel from the combustion chamber. Most notably, the orifices drilled into the injector will determine the mixture ratio of the propellants and, by extension, the combustion temperature, one of the most important components of rocket performance.

Fuel and oxidizer pool in the manifold above the injector plate at very high pressure - even higher pressure than the combustion chamber. The high pressure difference between the propellant manifolds (or, in the case of our current design as of 2022, just a fuel manifold as an oxidizer manifold is not employed) causes the propellants to be forced through the orifices at high speed.

The resulting narrow streams of propellant quickly splinter off into smaller droplets in a process known as “atomization”. Atomization can also be increased by colliding propellant streams, either unlike (Fuel and Ox) or like-on-like (Fuel and Fuel, Ox and Ox) collisions. Thorough and quick combustion is aided by thorough atomization of the propellants, which in turn will enhance the efficiency of the engine itself.

Ensuring the orifices are positioned to facilitate good mixing of fuel and oxidizer after propellant injection is also critical to ensuring that the propellants combust more thoroughly and quickly within the chamber. This consideration must be balanced with positioning higher temperature, less fuel-rich injector elements farther from the walls to reduce thermal loads placed on the chamber walls.

More in-depth information on designing injectors can be found in Sutton[1] on page 276. For the purposes of modeling the downstream chamber conditions induced by an injector, however, combustion efficiency can be assumed to be near-perfect and later adjusted for a given combustion efficiency factor (i.e. 80%). This topic will be covered further in additional documentation for future injector redesigns, and may also be read about more in [this](https://drive.google.com/file/d/1zOXj4d6CSSd0D4SrvRVpWDo5wtiENjzG/view?usp=sharing) excerpt from Sutton [A] as well as Section 8 in general of Sutton [1].

When modeling the combustion chamber though, a relatively safe assumption is that the combustion will effectively be complete for the purpose of temperature and pressure approximation. Thus, it is only necessary to retrieve from the injector the mass flow rates of each propellant through the injector plate.

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## Single-Phase Incompressible Flow through an Orifice

Determining the mass flow rate through an individual orifice across the injector is a relatively simple matter compared to modeling other aspects of the engine. Note that the flow through the nozzle is *assumed* not to be sonic/choked due to the relatively high speed of sound through the liquid propellants and comparably low injection speed by comparison.

With this in mind, the following equation 8-1 from Sutton pg. 280[1] can be used to model the non-sonic, non-cavitating mass flow rate through a single orifice.

(1)

Where:

* is the mass flow rate through the orifice in [kg/s]
* is the dimensionless discharge coefficient varying by orifice and fluid
* is the minimum area of the orifice
* is the inlet density in the orifice
* is by convention the upstream pressure in the manifold
* is by convention the downstream chamber pressure

Note that: the discharge coefficient generally varies with the shape of the orifice, as is approximated in [this excerpt of Sutton](https://drive.google.com/file/d/1zOXj4d6CSSd0D4SrvRVpWDo5wtiENjzG/view?usp=sharing) [A], and the manifold pressure can, for pressure-fed rockets, be assumed to be equal to the tank pressure *if* the total area of all the fuel inlet orifices in the injector is less than approximately one quarter of the minimum feed line area between the tank and the manifold.

Often this equation/flow model will be referred to as the Single-Phase Incompressible model, or SPI model. While this model *can* be used to approximate flow of a saturated liquid into a chamber below its vapor pressure by replacing with the liquid vapor pressure as extracted from thermodynamic tables/CoolProp, but this approximation tends to undershoot the vapor pressure moderately to severely. However, most propellants have a low enough vapor pressure that the SPI model is sufficient.

Also note that this equation determines the mass flow for each orifice, and must be summed for each orifice to find total mass flow through the whole injector. However, since and will remain relatively constant across the manifold, equation 2 below will factor out to be…

(2)

(3)

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## Conservation of Energy Modeling of Orifice Flow

When considering gaseous and multi-phase flow through an orifice, density becomes variable. Therefore, the incompressible SPI equation above no longer applies. Another means of predicting the flow rate is to consider the specific enthalpy drop of the fluid as it flows isentropically from the high pressure tank to the low pressure chamber. The rest of the flow rate is derived from the conservation of energy and definition of mass flow rate, as described in a simplified fashion below.

(4)

(5)

(6)

(7)

The downstream enthalpy must be extracted from a thermodynamic table or library (such as CoolProp[B]) at some given specific entropy at tank conditions, , which remains constant to the outlet at . The upstream specific enthalpy can be extracted from the same thermochemical library for tank temperature and saturated liquid or at given tank pressure . This model does a much better job of accounting for the flow rates of mostly-vapor injection, i.e. chamber pressure is far lower than vapor pressure at the outlet, but generally is known to underestimate the mass flow rate in rocketry applications, sometimes by up to 20%.

## Two-Phase Injection Mass Flow

In order to account for the fact that liquid injection is governed by both the principles of the HEM (vapor) model and the SPI (liquid) model, the Dyer model outlined by Zhang[2] accounts for both by making a linear combination of the two models multiplied by a dimensionless parameter .

(8)

The Dyer model for mass flow rate through an orifice can be applied as a linear combination of the two models. The two-phase mass flow rate can simply be expressed as:

(9)

(10)

Where:

* is tank pressure
* is chamber/downstream pressure
* is the vapor pressure in the tank
* is the dimensionless vapor fraction coefficient
* is the mass flow rate dictated by the SPI model
* is the mass flow rate dictated by the HEM model

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## Obtaining Vapor Pressure using CoolProp

CoolProp can be employed to find the vapor pressure relatively easily by calling on its saturated two-phase mixture data. Specifically, the vapor pressure or saturation pressure can be found by calling the pressure of a saturated vapor at the given temperature of the fluid. The command to call the pressure of such a fluid from CoolProp is as follows:

*py.CoolProp.CoolProp.PropsSI(“P”, “T”, Temp, “Q”, 1,* “*fluidName*”*)*

…as outlined by existing CoolProp documentation [here](https://docs.google.com/document/d/1SwY_JbAcMK3dY37hVzANKK0KHyNtMjkAvfUAsUOoy1Y/edit?usp=sharing)[B]. This command returns the pressure “P” at a given temperature *Temp* for the fluid *fluidName* of a vapor quality (i.e. percent in gaseous state) of 100%, which in turn is the partial pressure a saturated fluid will provide at a given temperature *T*.

## References and Sources

[1] [Sutton, Rocket Propulsion Elements](https://drive.google.com/file/d/1muyScRo6bWxT6AzNZnpIaxudrqsAPFAy/view?usp=sharing)

[2] [Zhang, Flow of Nitrous Oxide](https://drive.google.com/file/d/13sgYy71OLxnoVgRrm6HcxXP3CUkgUalK/view?usp=share_link)

## Related Documentation

[A] [Abridged Sutton Excerpt](https://drive.google.com/file/d/1zOXj4d6CSSd0D4SrvRVpWDo5wtiENjzG/view?usp=sharing)

[B] [CoolProp Quick Reference](https://docs.google.com/document/d/1SwY_JbAcMK3dY37hVzANKK0KHyNtMjkAvfUAsUOoy1Y/edit?usp=sharing)