DEVELOPMENT OF A FILM-COOLED THRUST CHAMBER COMPONENT IN THE ESPSS LIBRARY

Pierluigi Concio (1), Simone D'Alessandro (2), Francesco Nasuti (3)

(1) Sapienza University of Rome, Via Eudossiana 18, 00184 Italy, Email: pierluigi.concio@uniroma1.it
(2) Sapienza University of Rome, Via Eudossiana 18, 00184 Italy, Email: simone.dalessandro@uniroma1.it
(3) Sapienza University of Rome, Via Eudossiana 18, 00184 Italy, Email: francesco.nasuti@uniroma1.it

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ABSTRACT:

Active chamber cooling systems are often required in liquid rocket engine designs to suitably extract heat from the hot-gas flow and maintain a reasonably low wall temperature. In the design process, numerical simulations are mandatory to reduce the number of expensive hot-firing tests.
In this paper, models and their implementation in the EcosimPro/European Space Propulsion System Simulation (ESPSS) framework concerning liquid and gaseous film cooling modelling developed since the '50s and available in open literature are briefly presented, paying particular attention to numerical and modelling aspects in liquid rocket engines combustion chambers and nozzles.

1. INTRODUCTION

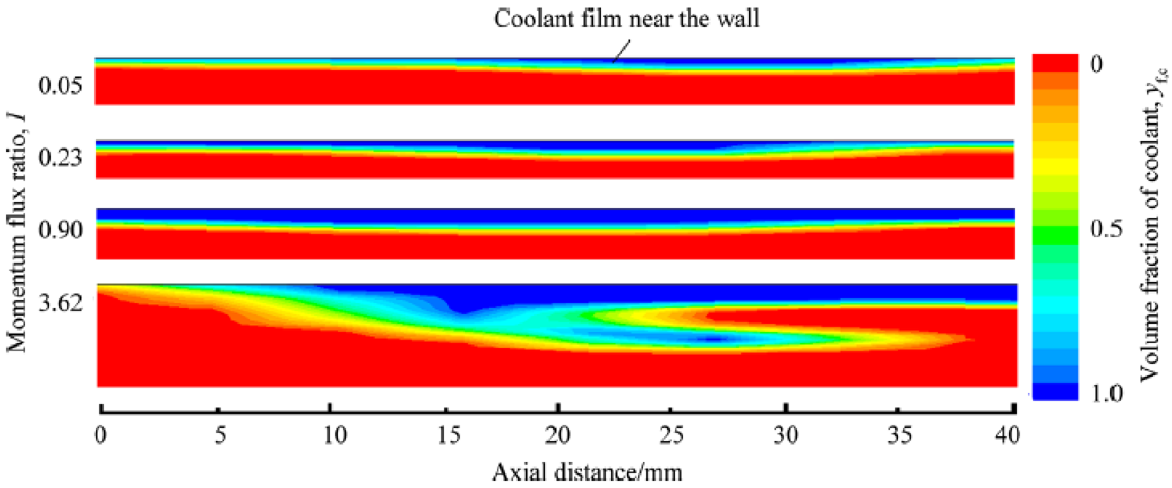
Film cooling is a cooling method used in liquid rocket engines to protect combustion chamber and nozzle walls against high thermal loads. A controlled flow of coolant is introduced either in liquid or gaseous phase as a thin film through slots or discrete holes, placed in the combustion chamber, for example at the outer row of the faceplate or at different positions downstream, or in specific nozzle planes toward the throat. The amount of mass flow rate that is typically used for this purpose is in the range between 1 and 6% of the total mass flow rate, yielding of course some performance loss. Film cooling might represent an interesting choice, especially when in combination with other cooling techniques such as regenerative cooling, achieving high performances and protecting those engines which operate at significantly high pressure, and thus undergo significantly high thermal loads.
To select some interesting liquid rocket engine (LRE) thrust chamber film cooling models to be implemented in the EcosimPro/ESPSS framework, an extensive research has been performed, covering experimental studies and modelling. Also, the first studies in the early '50s and the first feasibility studies both in LRE combustion chamber and nozzle have been considered.

The EcosimPro/ESPSS framework allows the system to be assembled by connecting the individual components available in the software, and furthermore it allows to design and develop brand-new components to be included in the model in turn. The final aim of this activity is then to develop a new component based on a film-cooled thrust chamber, in order to enrich and improve the heat loads prediction capability of the ESPSS simulation platform.
Suitable film cooling modelling is presented focusing on its compatibility with the EcosimPro paradigm, together with some qualitative results obtained during the activity conducted so far. That is followed by concluding remarks which summarize the most important aspects in view of the complete implementation of models in the EcosimPro platform.

2. LIQUID FILM COOLING

Liquid Film Cooling (LFC) is being studied since the early '50s, trying to understand the effect of different injection configurations and coolants on the film cooling performances in the first place, and then to assess its applicability to rocket applications [1-9]. The latter was guaranteed by early feasibility studies [1-3, 8, 11, 13], in which significant wall heat flux reduction was observed with acceptable performance losses in terms of specific impulse of both storable and cryogenic propellants. Those kinds of propellants, such as hydrazine-type propellants, hydrogen, and methane, were considered more suited for film cooling of rocket engines than other coolants used in the past years [3], due to high heat of vaporization and high heat capacity in gaseous phase, respectively.
Only few experimental studies on LFC under rocket engine-like conditions are available. Nevertheless, different propellants such as hydrogen [8], space storable [10], and hydrocarbons [11, 12] and have been employed, even at high pressures up to 138 bar, to test the heat flux reduction due to LFC. Three peculiar and particularly challenging aspects can be defined for LFC, i.e. the liquid film stability, its phase change (evaporation), and the Film Cooled Length (FCL). In particular, the FCL is defined as the length after

which the film ceases to exist in liquid phase, thus



changing completely the cooling performances.

Figure 1. Liquid-gas interface shapes at different momentum flux ratios. [24]

The determination of the evaporation rate for both inert and reactive coolants was the object of the early analytical and empirical studies on LFC [15, 16]. A lot of assumptions, such as stable liquid film, were retained to obtain results in closed form. Eventually, models were also calibrated on the basis of very specific experimental data, yielding very limited applicability in some cases [7, 17, 18]. Unrealistic treatments of film stability led also high discrepancies in later numerical studies [19]. Different attempts have been made to develop correlations accounting also for the entrainment of liquid droplets in the gaseous phase. Gater et al. [20] correlated the mass and energy transfer due to vaporization and unvaporized liquid entrainment with the Stanton number and the coolant flow rate, strictly relying on experimental data on liquid-gas interfacial structure and interaction. Unfortunately, further experimental data have never been available to prove their technique. Stechman et al. [3] calculated the turbulent heat transfer coefficient between the liquid film and the wall analytically by means of a modified Bartz equation, obtaining a 20% error. Corrections to the equation were introduced to include film instability, the two-phase nature of the flow and the variation of transport properties between the main core gas and the coolant. Nevertheless, the model was found to provide good results only in case of small engines.
A correlation yielding good yet limited results has been recently developed by *Sawant et al.* [21], who correlated the liquid entrained fraction with Weber and coolant Reynolds numbers. However, the correlation was developed relying only on air-water test data, hence there is still a need for improvement considering fluids with different properties. Even nowadays, the liquid entrainment and film stability phenomena are not understood enough to give definitive conclusions [22, 23], and no experimental information is available for assessment under rocket engine-like conditions. Nevertheless, Shine et al. [24] were able to observe the liquid surface shearing due to disturbance waves by means of transient numerical simulations, and to identify that as the main mechanism of liquid entrainment (see Fig. 1).
From the modelling point of view, the correlation by Sawant et al. [21] represent the better choice for liquid entrainment fraction evaluation. A very simple expression is used to correlate the entrained liquid fraction with the coolant Reynolds number and a modified Weber number:

$$E = E_m \tanh(aWe^{1.25}) \qquad \text{Eq.1}$$

$$a = 2{,}31 \times 10^{-4} Re_L^{-0{,}35} \qquad \text{Eq.2}$$

$$E_m = 1 - \frac{250\ln(Re_L) - 1265}{Re_L} \qquad \text{Eq.3}$$

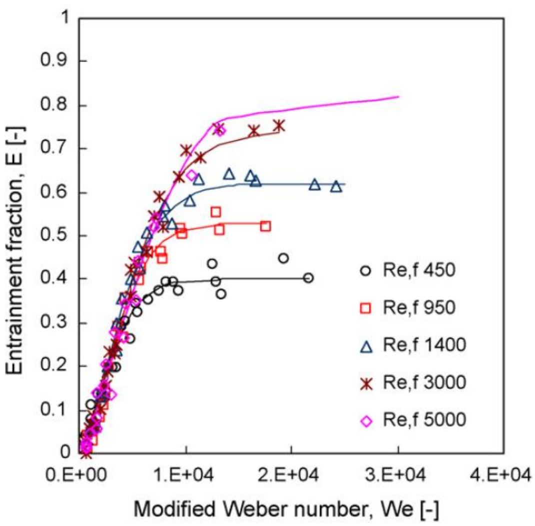


Figure 2. Comparison of the correlation by Sawant et al. [21] with experimental data [21].

where E is the entrained fraction, We the Weber number, Re the Reynolds number, subscript L refers to liquid phase. Those two non-dimensional parameters were found to successfully collapse the experimental data (see Fig. 2). Experiments were conducted within a limited pressure range, up to 6 bars, and for several coolant flow rates. This correlation provides a simple and direct calculation of the entrained fraction without any iterative procedure, hence yielding ease in calculation and low computational effort, which are required for the implementation in EcosimPro.

Liquid entrainment was also included in semi-analytical models developed for the determination of the FCL. Ewen and Evensen [25] proposed a compact expression, in which the FCL is calculated as a function of the coolant flow rate and a liquid entrainment parameter. The latter is based largely on empirical correlations, and depends on both phases and interface properties, such as density, velocity, temperature, and surface tension. This model, together with that by Stechman et al. have been applied to an oxygen/kerosene combustion chamber by Trotti [26], showing an overall overestimation and, in general, a discrete matching. Grisson [27] developed a 1-D model for the determination of the evaporation rate and FCL also including the effect of radiation in a rocket thrust chamber. Liquid entrainment and flow acceleration effect were neglected, making this model valid only at low coolant flow rates. The model employs a LFC treatment until the film dry-out point, after which the coolant is considered as a gas. Relying on experimental data [1, 4, 10], wall temperatures were well predicted upstream of the convergent entrance. After the nozzle entrance, a correction term accounts for the increased mixing due to the geometry. Further downstream results are not comparable due to the lack of modelling concerning flow acceleration effects. This model has been recently adapted by *Jang et al.* [28] to calculate the FCL in a H_2O_2/RP-1 bi-propellant thruster. The model was kept essentially unchanged, but, in addition, thermal decomposition of H_2O_2 was taken into account by means of an empirical constant, and it was observed how this process caused a reduction of the FCL. The 1-D model by Grisson [27] foresees an iterative procedure to determine the FCL (Fig. 3), as the abscissa where the liquid flow has completely vaporized. Afterwards, gaseous film cooling modelling should be adopted. After calculating the radiative heat flux between the main stream and the film interface, the first step of Grisson's model is to calculate the heat transfer coefficient between the wall and only the main stream, which is a function of the Reynolds and Prandtl numbers and hot-gas density, velocity and heat capacity. This coefficient is then corrected by adding the effect of transpiration, in fact the vapor which flows away from the liquid film causes a decrease in wall heat transfer. The vaporized coolant flow and the heat transfer itself are eventually calculated iteratively.

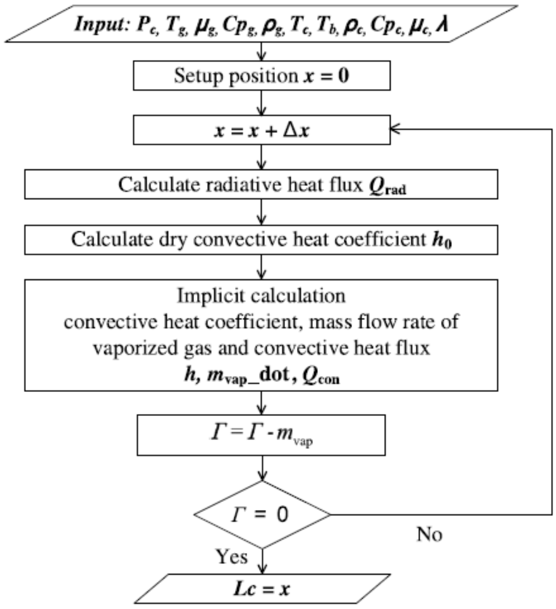


Figure 3. Flowchart of the FCL calculation according to Grisson [27].

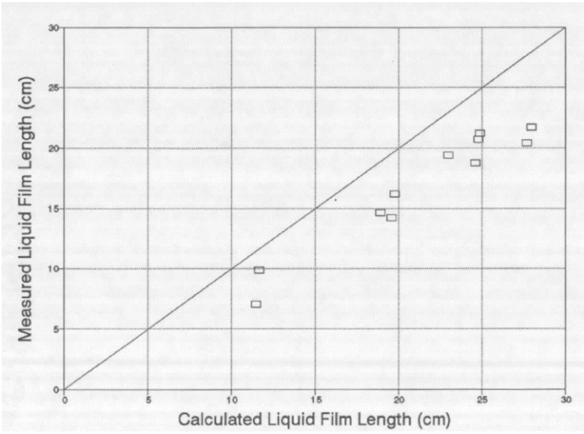
A further model has been provided by Shine et al. [29], who developed a semi-analytical model including both radiation and liquid entrainment for chambers operating at subcritical pressures. Correlations by Sawant et al. [21] and Leckner [30], respectively for entrainment and gas total emittance, were employed. Among all, results have been compared also against the same experimental data used by Grisson [1], showing better agreement (see Fig. 4). Although further work and more detailed experimental data are required to extend the model to reactive coolants, this model provides the most accurate FCL prediction, with errors between 9% and 15% with respect to experimental data.

The model by Shine et al. [29] follows essentially the same steps of Grisson but introducing some differences. The value of the convective heat transfer coefficient without transpiration (h_0) is calculated iteratively starting from the Reynolds number via the Darcy friction factor f_D:

$$\frac{1}{\sqrt{f_D}} = 1.93\, log(Re\sqrt{f_D}) - 0.537 \qquad \text{Eq.4}$$

Moreover, a correction factor depending on the hot-gas and coolant molar mass ratio M_w is added to the transpiration correction for the convective heat transfer coefficient:

$$h = \mathrm{F}(h_0, H, M_w) \qquad \text{Eq.5}$$



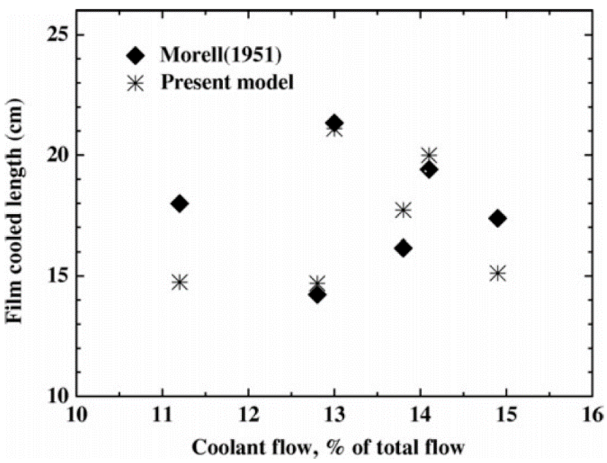


Figure 4. Comparison of LFC results by Grisson [27] (left) and Shine et al. [29] (right) against experimental data [1].

where H is a function of the evaporation rate and other model parameters. The improved accuracy with respect to the Grisson's model [27] is attributed to the calculation of the entrainment fraction, obtained according to Sawant et al. [21]. The latter consists in simple and direct operations, which should not significantly increase the computational effort. The FCL is obtained by dividing the difference between the total coolant flow rate and the entrained flow rate by the coolant vaporization rate.
As can easily noticed, those models introduce some heavy computations, such as the implicit calculation of several quantities, which require further iterative procedures to be calculated. Concerning the simulation time, such an operation may result in an excessive slow-down of calculations when the new component will be integrated in a complex system as a rocket engine could be. A solution to this problem could be considering a simpler model which foresees direct calculations, accepting a compromise between accuracy and computational cost. The model proposed by Ewen and Evensen [25] may be a choice since no implicit calculations are required. Nevertheless, functional dependencies are very complicated, making the model complexity and required computational resources still high.
A simple model which can be considered for the implementation in EcosimPro is provided by Grisson himself [27], which also considered the case in which radiation is negligible. This may result in a significative simplification and reduction of accuracy, because, even if radiation can be actually negligible in rocket engines under certain conditions of pressure and size, it may significantly affect the transpiration process in case of high main stream temperature. If radiation is not present, the calculation of the convective heat transfer coefficient is explicit. In this way, the calculation of the FCL and the transpiration correction to the convective heat transfer coefficient become much simpler and affordable for implementation in EcosimPro.
Very few numerical studies based on CFD are available [31-34]. Nevertheless, they allowed to study the behaviour of LFC when integrated in regeneratively cooled engines. The current computational efforts are mainly based on RANS computations. Since CFD is not directly compatible with EcosimPro, details are not provided here.
So far, no research activity is available on liquid film cooling under supercritical conditions in rocket thrust chambers.

3. GASEOUS FILM COOLING

Similarly to LFC, the study of Gaseous Film Cooling (GFC) started in the '50's with investigations dedicated to understand the effects of different coolant injection procedures on the main stream boundary layer [35-40], until the first feasibility studies performed in rocket combustion chambers and nozzles [41, 42]. Hydrogen, methane, and also nitrogen and propane were used as coolants, realizing that the former are more suitable for rocket applications. Moreover, multi-slot coolant injection was found to be more suited for high energy propellants in rocket applications as well. In this framework, turbulence and compressibility effects on film cooling performances have been largely discussed in the literature. A significant great decrease in the film cooling performances was found to occur with an increase of the free stream turbulence level first by Carlson and Talmor [43] in the late '60s and then by Gau et al. [45] in the '90s, whereas no significant consequences occur changing the turbulence intensity of the coolant jet [46]. On the other hand, compressibility effects were considered negligible as a first approximation in combustion chambers for a wide range of velocities and temperatures until the early '70s [47, 48].

Opposite results have been found experimentally by Pedersen et al. [49] and Hansmann et al. [50] within the following 20 years, according to which density and velocity ratios have a considerable influence on the film cooling effectiveness. Eventually, Dellimore et al. [51] confirmed this statement showing that flow compressibility changes the growth rate of the shear layer between the main and secondary flow. They also attributed the contradictory results obtained in the past to the use of a low Mach number.

Few yet significant experimental studies under different rocket engine-like conditions have been recently developed [52-55], also providing a great amount of data for validation of numerical tools. Hydrogen, methane, and kerosene were employed as coolants under low, medium and high-pressure conditions for different chamber and injection slot geometries. The assessment of the role played by blowing ratio, i.e. the ratio between coolant and main stream mass fluxes, coolant mass flow rate, slot dimensions, and out-of-plane motions on film cooling performances was the main goal of these campaigns.

Experimental information is available also in the framework of supersonic GFC. One of the first goals was that of Goldstein [56] in the ‘60s to study the effect of the blowing ratio on the adiabatic wall temperature using a single slot for coolant injection. Important developments were made in the ‘90s, when Juhany et al. [57] showed that cooling effectiveness improves with increasing injectant Mach number and heat capacity. A large amount of data was produced in the following years by Aupoix et al. [58], considering different geometries, pressure ratios and film temperatures. They observed the improvement on film cooling efficiency in supersonic conditions due to reduced mixing, thus confirming Juhany et al.’s results [57]. Further studies were performed recently on the effect of the coolant jet on flow separation in TOC nozzles [59] and the decrease of film cooling effectiveness in presence of an impinging shock waves [60].

Concerning the modelling, the determination of GFC performances has been mostly carried out empirically. Several correlations have been proposed [61-65], typically in terms of film cooling effectiveness, which represents the capability of the coolant jet to thermally insulate a surface. Unfortunately, among the many studies and results available in open literature about GFC, only few recent numerical analyses addressed rocket thrust chambers. Early studies were dedicated to the study the applicability of GFC and, in particular, to correlate the film cooling effectiveness with the injection procedure. As described in detail by Goldstein [66], investigations expressed empirically the cooling effectiveness as a function of the blowing ratio, fluid properties, distance from the injector and the Reynolds number, using very similar mathematical expressions, for instance:

$$\eta = \frac{1}{1 + 0.329\left(c_{p_\infty}/c_{p_c}\right)\xi^{0.8}} \quad \text{Eq.6}$$

$$\eta = \frac{1}{1 + \left(c_{p_\infty}/c_{p_c}\right)[0.329(4.01 + \xi)^{0.8} - 1]} \quad \text{Eq.7}$$

$$\xi = \left(\frac{x}{Ms}\right)\left[\frac{\mu_c}{\mu_\infty}Re_c\right]^{-0.25} \quad \text{Eq.8}$$

$$M = \frac{(\rho u)_c}{(\rho u)_\infty} \quad \text{Eq.9}$$

where η is the cooling effectiveness, c_p the thermal capacity, M the blowing ratio and s the slot dimension. These models [62-65] assume constant properties ideal gases, a constant average temperature in the boundary layer, and a full mixing of the coolant with the main stream. Good agreement was found against experimental data though, due to a sort of counterbalancing effect introduced by the last two assumptions. A significant improvement was made by Goldstein and Haji-Sheikh [67], who tried to correct the assumptions relying on experimental data, made in the past. New dependencies were proposed, such as the coolant molecular weight, Prandtl number, and angle of injection. Comparisons with experimental data proved that such modeling were able to provide better results then the previous modeling techniques. Other empirical models were developed, always providing worse results than Goldstein and Haji-Sheikh [67]. Hatch and Papell [68], for instance, developed an experimentally-assessed correlation relying again on the assumption of fully mixed flow, even in case of angled injection. Several years later, the model was considered valid also in case of multiple injection of coolant by Sellers [69], but some aspects remained still fairly questionable. Spalding [70] proposed instead a piecewise defined correlation to describe the film cooling effectiveness drop downstream the film breaking point, but the model was limited only to injection parallel to the wall. On the other hand, recently, Arnold et al. [71] claimed that none of the previous models considered the extreme conditions inside a rocket thrust chamber and the acceleration due to a high pressure gradient in presence of a fully turbulent, high temperature flow with variable properties. A modified empirical correlation was hence developed for the film cooling effectiveness on the basis of that by Goldstein and Haji-Sheikh [67]. The correlation is shown in Eq.10. Flow acceleration effects were included by adapting the approach initially proposed by Hartnett et al. [62] to the chamber environment.

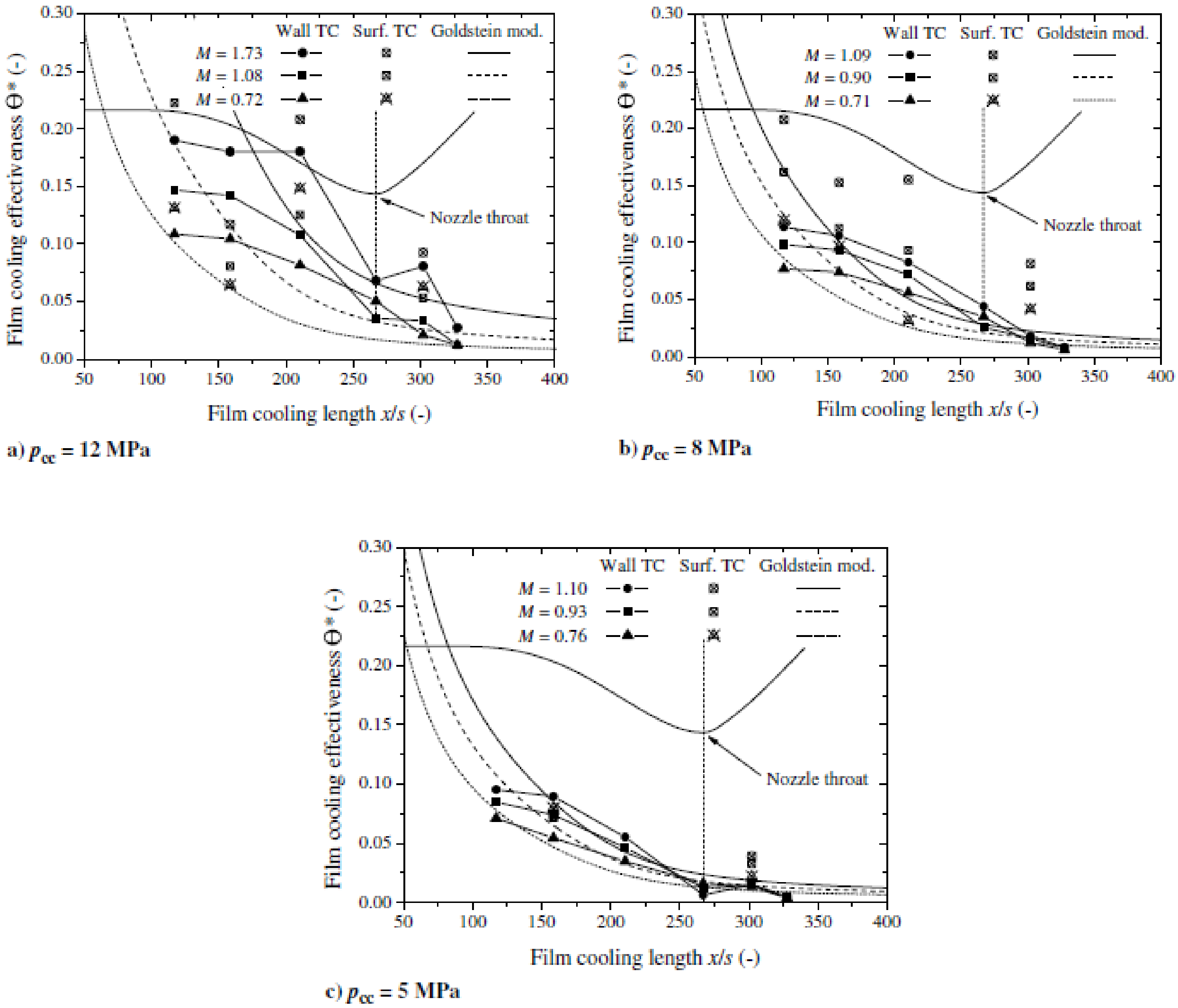


Figure 4. Film cooling effectiveness at different chamber pressures. [71]

$$\Theta(x) = \frac{T_{w,0}(x) - T_{w,f}(x)}{T_{w,0}(x) - T_c} = \frac{0.83 Pr^{2/3}}{1.11 + 0.329 \left(\frac{c_{p_{hg}}}{c_{p_c}}\right) \left(\frac{x}{Ms}\right)^{1.43} Re_c^{-0.25}} \quad \text{Eq.10}$$

The actual cooling effectiveness is obtained by multiplying the quantity $\Theta(x)$ by a function of the local Mach number to account for flow acceleration and compressibility effect.

Assessments have been done with experimental data by the authors themselves, showing good agreement under typical conditions of liquid rocket engines (see Fig. 4).

Instead of LFC, for which there is not a choice clearly better then another, the model by Arnold et al. [71] can be considered very suitable to be implemented in EcosimPro, due to direct and simple calculations and ease in obtaining the wall temperature from the correlation. The only difficulty is that a second simulation is needed to carry out the final film cooling evaluation, since a first run without coolant is fundamental in order to compute the quantity $T_{w,0}(x)$.

The last model presented here has been recently already considered a good choice for implementation in EcosimPro. The model, developed by Simon [72], expresses the film cooling effectiveness as a function of coolant mass flow rate, main stream turbulence level, and coolant and main stream temperatures. Experimental data were considered for comparison and for the empirical model closure. The wall-jet region and the fully developed region were dinstiguished by interposing a fully mixed region in between. Important conclusion were drawn by Dellimore et al. [51] by improving Simon's model including the effects of adverse and favorable pressure gradients and flow compressibility as briefly described above. In particular, the velocity

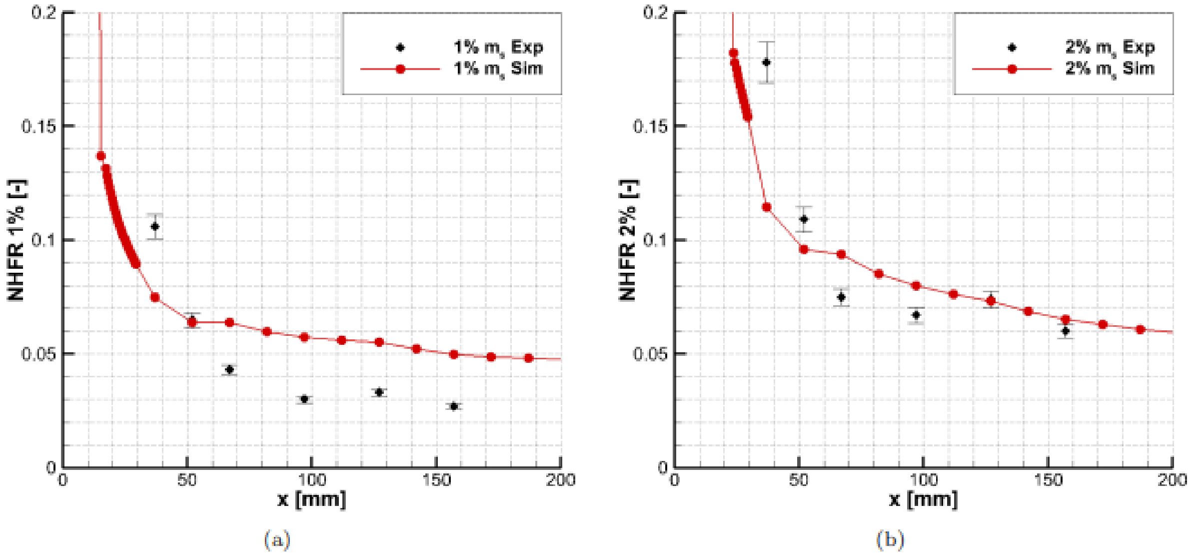


Figure 5. Net Heat Flux Reduction predictions for (a) 1% and (b) 2% film mass flow rate. [73]

ratio was found to control the film cooling performance in presence of a pressure gradient. Simon's equations and geometry were retained by Di Matteo et al. [73], who developed a new model by adding the effect of variable heat capacity with temperature, presence of two different fluids and high temperature ratios. The model has been implemented in EcosimPro using the ESPSS libraries, and results have been validated against oxygen/hydrogen experimental data [54], showing qualitatively good agreement (see Fig. 5). As for LFC, few numerical CFD studies are available in literature. Again, RANS-based approaches were preferred to study the film cooling performances both in combustion chambers [74-78] and nozzles [79-82]. LES or DNS approaches have never been applied to GFC under rocket engine-like conditions.

4. IMPLEMENTATION

Several film cooling models have been selected as best candidates to be implemented into the platform [27, 29, 71, 73]. The reasons for choosing different models are different. First, since the underlying phenomena are different, different models are needed. Thus, both modelling families need to be implemented in the framework. Secondly, the different levels of insights, required by the different kind of analyses which one might want to carry on, might need different levels of modelling detail, especially when dealing with liquid cooling models. For such a reason, models capable of providing different levels of fidelity have been chosen to be implemented.

As a demonstration of a qualitative the full and simplified Grisson's models [27] have been implemented and simulated using a simple configuration with an oxygen/methane film-cooled thrust chamber directly connected to tank conditions. Focus is on the main model parameters, i.e. evaporation rate, and total heat load at the wall.

Reasonable results are obtained with full Grisson's model. As shown in Fig. 6, the coolant is observed to evaporate in the first half of the chamber, where evaporation rate is different from zero and the liquid mass flow rate progressively decreases.

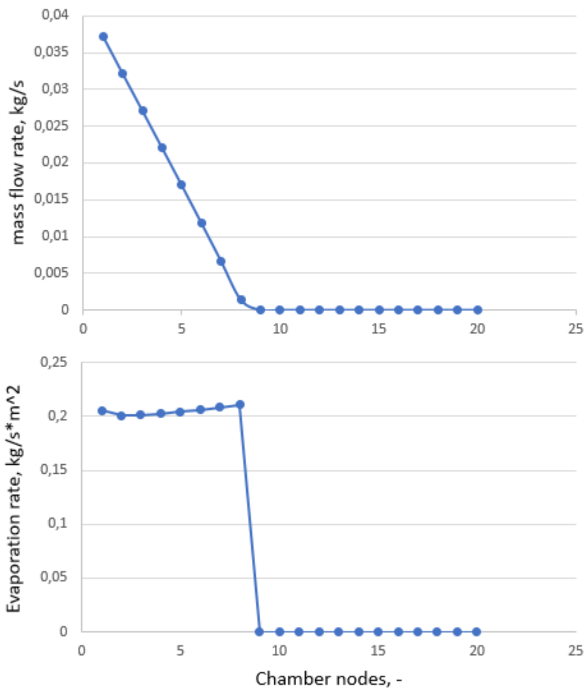


Figure 6. Liquid coolant mass flow rate per unit circumference (top) and evaporation rate (bottom) along the combustion chamber.

In such model, the coolant is expected to exchange heat with either the hot-gas and the wall during heating and evaporation. Since the coolant saturation temperature is lower than the ambient temperature enforced at chamber wall, the convective wall heat flux exchanged by the liquid film and the chamber wall is expected to enter the film, and thus to be negative before complete gasification, as shown in Fig. 7.

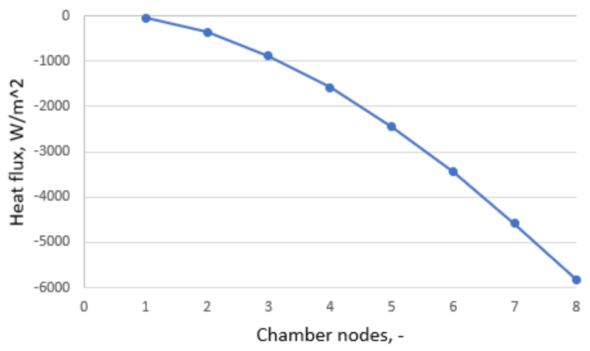


Figure 7. Convective wall heat flux during coolant evaporation. Particular on the first nodes.

Once the coolant has vaporized, the film continues to provide thermal protection to the wall by calorimetric mixing with the hot gas entrained in the boundary layer. Fig. 8 shows the total heat at the wall, i.e. the sum of convective and radiative contributions. Bartz equation applies in the nozzle, that is after the twentieth node.

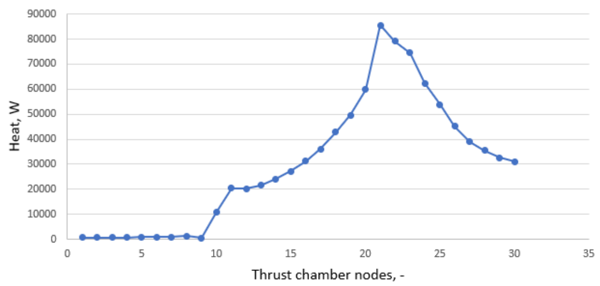


Figure 8. Total heat at the wall along the thrust chamber.

Differently from the full model, the simplified Grisson's model does not consider radiative contribution to total heat flux, providing an explicit formulation for the FCL. Therefore, no space integration is needed to detect complete gasification, and the liquid film can be reasonably considered a control volume with constant properties, as supposed by Shine [29] as well. As opposed to Grisson's full model, as a further simplification no heat exchange is assumed to occur between the liquid film and the wall, making the hot gases the only heat source in the model.
As shown in Fig. 9, the evaporation rate is lower than that obtained with the full model since the radiation and convective contribution from the ambient are absent. Moreover, that yields also a higher FCL due to the lower amount of heat absorbed by the liquid film.

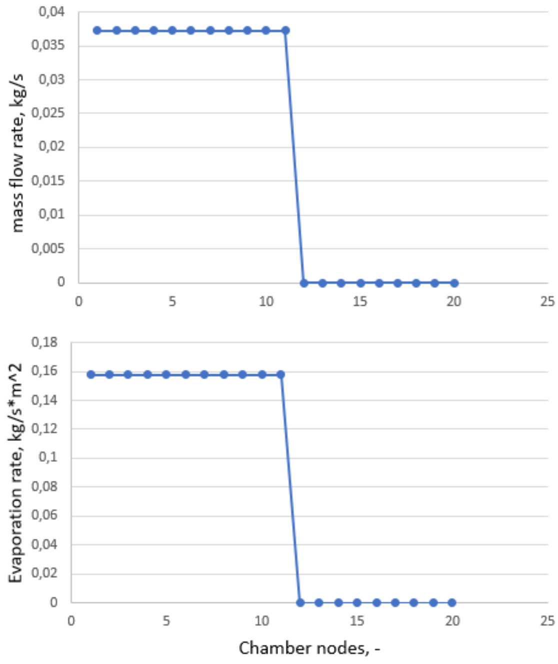


Figure 9. Liquid coolant mass flow rate per unit circumference (top) and evaporation rate (bottom) along the combustion chamber. Simplified model.

5. CONCLUSIONS

From the results presented in this paper, it can be concluded that a reliable and accurate prediction of film cooling needs a model capable to describe the phenomenology in all its aspects. Moreover, different modeling is required due to the different underlying phenomena and due to the sought level of approximation.
Liquid film cooling appears to be a complex phenomenon to be represented in a 1D modelling framework due to the high complexity of phenomenology, which might lead to computationally heavy formulations. Some models have been selected for implementation. The model by Grisson in particular is found to provide a reasonable prediction of the phenomenology occurring in the thrust chamber. Nevertheless, a higher level of model completeness might be required to take into account some relevant aspects as the entrainment of liquid phase in the main stream. So higher accuracy in the calculation of FCL may be achieved using the Shine model, which accounts for liquid entrainment and is expected to be implemented as the next step of this activity. Accurate results are expected from these two models but involving heavy computations. More approximate results results are expected using the simplified Grisson's model, thus offering the possibility to make a choice between a more accurate and a quicker calculation.
Concerning gaseous film cooling, the situation is easier. Besides the gaseous formulation by Grisson, the semi-analytic model by Arnold has been considered a satisfactory formulation dealing

with the rocket thrust chamber phenomenology, especially in the nozzle since it accounts for flow acceleration. Moreover, it is well assessed against a wide range of chamber pressure. Good results are expected also the model by Di Matteo, which has been already considered suitable for the implementation in Ecosimpro and, moreover, it is well assessed against experimental data.

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