



Research Paper

Thermal analysis and modelling of cryogenic coolant flow in an aerospike engine additively manufactured cooling channel

Nikos Monokrousos ^a, László Könözy ^a,*, Vassilios Pachidis ^a, Ernesto Sozio ^b, Federico Rossi ^b

^a Cranfield University, College Road, Cranfield, Bedfordshire, MK43 0AL, United Kingdom

^b Pangea Aerospace, Avinguda Número 1, 20 08040 Barcelona, Spain

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ABSTRACT

Cryogenic propellants play a crucial role in regenerative cooling systems of liquid rocket engines, particularly in high-heat flux applications such as aerospike engines. The present study is conducted within the framework of the DemoP1 demonstrator, a 20 [kN] LOx/LNG Additively Manufactured (AM) aerospike engine developed by Pangea Aerospace. This work aims to present a numerical characterisation of the cryogenic liquid oxygen flow within an AM cooling channel of the DemoP1 demonstrator. To analyse the development of the fluid primitive variables, the objective of this study is to provide a detailed assessment of the thermophysical properties and dimensionless numbers governing the cryogenic flow. The numerical findings are compared against experimental data obtained from the full-scale, single-injector hot-fire testing campaign of the demonstrator. The results highlight the enhanced heat transfer performance of AM cooling channels with high process-inherited roughness compared to conventional smooth-surface channels. Finally, a modified Dittus–Boelter correlation is introduced to characterise the heat transfer behaviour of the cryogenic flow in the AM channel. The case study presented here consists one of the first attempts to provide a comprehensive analysis on the cryogenic flow characteristics in the novel dual regenerative cooling system of an aerospike engine.

1. Introduction

The engineering area of cryogenic flow applications has been an active field of research over the past decades. Cryogenic flows are described by very-low temperatures and regard the understanding of the physical processes and changes of the fluid flow properties, furthermore to the deviations in the physical mechanisms of the materials bounding them. It is often referred in the literature that a cryogenic fluid is characterised by temperatures roughly below 120 [K] [1]. Common cryogenic fluids such as oxygen, hydrogen and nitrogen are employed in various industrial, biomedical, maritime and aerospace applications [2–5]. A significant advantage offered in cryogenic applications regards the transport of the cryogenic fluids, as it is preferable to transport a liquid-phase fluid in atmospheric pressure vessels, than a gaseous fluid in high pressure, requiring high thickness vessel walls to be contained. Therefore, the utilisation of cryogenic coolants in high-heat flux, high-pressure aerospace applications is a very common practice.

1.1. Cryogenics in aerospace applications

Cryogenic temperatures are very commonly encountered in aerospace applications, requiring the fluid management and manipulation of very-low temperature fluids. Amongst the most suitable candidates for aerospace applications such as spacecraft components cooling, space exploration, human spaceflight and in-situ resource utilisation are the cryogenic liquid oxygen, nitrogen and methane. Cryogenic applications are also found in a wide range of stages in the field of aviation [6–9]. Furthermore, cryogenic flows are often encountered in liquid rocket engine applications. For instance, cryogenic flows such as liquid oxygen, hydrogen and methane constitute the key candidates for the new generation of large-thrust rockets [10–13], due to their favourable properties for the satisfaction of the requirements of such high-heat flux aerospace applications. A comprehensive review of recent advancements in theoretical establishments, methodologies and state-of-the-art applications for cryogenic fluids is presented in [14].

An important metallic component for high-heat flux aerospace applications is the regenerative cooling system of liquid rocket engines.

* Corresponding author.

E-mail address: laszlo.konozsy@cranfield.ac.uk (L. Könözy).

Nomenclature**Abbreviations**

AM	Additive Manufacturing
ARS	Approximate Riemann Solver
BSL	Baseline
CFD	Computational Fluid Dynamics
FANS	Favre–Averaged Navier–Stokes
L-PBF	Laser-Powder Bed Fusion
LOx	Liquid Oxygen
RMS	Root-Mean-Square
SLM	Selective Laser Melting
SST	Shear Stress Transport
STD	Standard
UDF	User-Defined Function

Symbols

$\dot{m}$	Mass flow rate
D_h	Hydraulic diameter
A	Rectangular cross-section area
$c_{p,w}$	Solid specific heat capacity
c_p	Fluid specific heat capacity
EP	Evaluation profile of rough surface
E	Total energy of the fluid
F_d	Distance of floor profile from mean line
F_p	Average height of rough elements below mean line
f_r	Friction factor for rough surfaces
f_s	Friction factor for smooth surfaces
$h_{w,hg}$	Convective heat transfer coefficient from hot-gas side
H	Height of the microfluidic cooling channel
k_s	Equivalent sand-grain roughness height
k_u	Kurtosis
k_w	Thermal conductivity of the solid material
k	Turbulence kinetic energy
m	Mean line of evaluation profile
Nu_{corr}	Nusselt number correlation
Nu_r	Nusselt number for rough surfaces
Nu_s	Nusselt number for smooth surfaces
N	Total number of numerical measurements
Pr_t	Turbulent Prandtl number
P	Average coolant pressure
$q_{w,hg}$	Heat transfer rate from hot-gas side
R_a	Arithmetic mean deviation
R_p	Maximum peak height above mean line
R_q	Root-Mean-Square roughness
R_v	Maximum valley depth below mean line
R_z	Maximum peak to valley height
Re	Reynolds number
s_k	Skewness
T_{aw}	Adiabatic wall temperature
T_b	Bulk temperature
$T_{w,c}$	Coolant-side wall temperature
$T_{w,hg}$	Hot-gas side local chamber wall temperature
t_w	Width of solid material wall
T	Average bulk temperature

u	Average coolant velocity
W	Width of the microfluidic cooling channel
x_i	Coordinate in direction i
y_i	Roughness amplitude
y	Distance to the closest surface
z	Longitudinal coordinate

Greek Symbols

$(\tau_{ij})_{eff}$	Deviatoric stress tensor
α, β, γ	Nusselt number correlation coefficients
δ	Kronecker delta
μ	Dynamic viscosity of the fluid
μ_t	Fluid turbulent (eddy) dynamic viscosity
ν	Kinematic viscosity of the fluid
ν_t	Fluid turbulent (eddy) kinematic viscosity
ω	Specific dissipation rate
ρ	Density of the fluid
ρ_w	Density of the solid material
λ	Thermal conductivity of the fluid

A regenerative cooling system of a liquid rocket engine consists of cooling channels that surround the rocket engine, allowing for the cooling of the rocket engine wall boundaries from the high heat fluxes resulting from the gases of the combustion chamber. In high-heat flux aerospace applications, the high-roughness inherited by the manufacturing process can be beneficial and enhance the heat transfer capabilities of the cooling channels constituting the liquid rocket engine regenerative cooling system. A characteristic experimental campaign for the investigation of the performance of regenerative cooling systems in liquid rocket engines is the HYPROB program. The HYPROB program is implemented by CIRA, the Italian Aerospace Research Center under contract with the Italian Ministry of Research, focusing on the regenerative cooling system of a LOx/LCH₄ liquid rocket engine [15]. A preliminary review of the objectives and guidelines for the selection of liquid methane as the propellant of interest to be investigated in the test article of the HYPROB program experimental campaign is presented in [16]. Several numerical and experimental investigations have been conducted for the characterisation and modelling of the methane behaviour in the rectangular cross-section cooling channel of the test article developed within the HYPROB program. Prior to proceeding with the description of the methane propellant behaviour in the cooling channel of the LOx/LCH₄ liquid rocket engine regenerative cooling system, numerical building activities were performed for the implementation of an in-house solver for validation purposes. Pizzarelli et al. [17], performed a numerical investigation on the heat transfer behaviour of supercritical hydrogen flow in single- and double-curvature cooling channel. In their work, the authors validated their in-house Computational Fluid Dynamics (CFD) solver against experimental data on heated channels characterised by curvatures, concluding for the appropriateness of the in-house solver to be utilised for the validation of coolant flows in liquid rocket engines cooling channels. Subsequent to the validation of the in-house solver, the authors [18] proceeded with performing coupled computations of the coolant flow-field development by means of the validated Reynolds–Averaged Navier–Stokes (RANS) solver and the wall thermal conduction in the solid material. In the work of Betti et al. [19], the conjugate heat transfer model implemented considered the computations on the hot-gas side of regenerative cooling system of the thrust chamber, furthermore to the coolant-flow side and the wall conduction estimations. The results obtained from the coupled hot-gas-wall-coolant flow computations in the regenerative cooling system were in a reasonable agreement against nominal data available in the literature. Ultimately, Pizzarelli et al. [20,21] evaluated

the performance of a cooling channel comprising the LOx/LCH₄ liquid rocket engine regenerative cooling system. In their work, the authors investigated the heat transfer capabilities of the cooling channel under the influence of different levels of coolant mass flow rate, surface roughness and coolant pressure. The results indicated the significance of heat transfer phenomena such as heat transfer deterioration resulting from the coolant operation in near-critical conditions.

Numerous computational investigations have been performed for the description of the thermal behaviour of cryogenic propellants in liquid rocket engines. Ricci et al. [22] performed an experimental and numerical investigation on the behaviour of liquid methane propellant in a regenerative cooling system of a LOx/LCH₄ liquid rocket engine. In their work, the authors initially discuss the details of the HYPROB programme experimental campaign, before proceeding with the numerical solution of the liquid methane flow in a high-roughness cooling channel of rectangular cross-section, comprising the regenerative cooling system of a liquid rocket engine, and its comparison against experimental measurements obtained from the hot-fire testing campaign. In their work, Ricci et al. [23] presented a preliminary numerical rebuilding activity for the solution of the liquid methane propellant in transcritical conditions at the cooling channel of the LOx/LCH₄ liquid rocket engine regenerative cooling system. Subsequently, Votta et al. [24] proceeded with an in-depth study of the behaviour of transcritical methane propellant in the regenerative cooling system of a LOx/LCH₄ liquid rocket engine. The authors were able to obtain a numerical solution of the methane propellant in a high-roughness cooling channel of the liquid rocket engine and derive a peculiar Nusselt number correlation for the characterisation of the liquid propellant thermal behaviour. Numerical investigations from the perspective of the high surface roughness encountered in cooling channels of liquid rocket engine regenerative cooling systems have also been performed. In the work of Latini et al. [25], the authors derived an extension of the external flows roughness correction of the one-equation Spalart–Allmaras turbulence model and constructed a model accounting for phenomena arising in internal flows bounded in high roughness wall boundaries. Furthermore to the investigation of liquid methane propellant in liquid rocket engine cooling channels, Nasser et al. [26] investigated the heat transfer capabilities of regenerative cooling system channels for different mixtures of hydrocarbon impurities in the liquid natural gas propellant, offering a comprehensive understanding of the correlation between the Nusselt number of the investigated flow, the wall roughness of the cooling channel and the composition of the liquid rocket engine propellant. High roughness Reynolds number flows in cooling channels of liquid rocket engines have also been studied with respect to the determination of the friction factor and heat transfer characteristics in the work of Santese et al. [27].

1.2. Additively manufactured (AM) cooling channels for high-heat flux aerospace applications

The recent technological advancements in the field of Additive Manufacturing (AM) are a direct consequence of the ever-growing interest exhibited in the conceptualisation and development of novel high-heat flux aerospace applications. As a result, various private companies and research organisations focus their research and development efforts on the fabrication of metallic components using additive manufacturing techniques. A broad discussion on the importance and the benefits of the utilisation of AM technologies in the current space sector economy can be found in [28]. The fabrication of complex metallic components such as regenerative cooling systems for combustion chambers of liquid rocket engines has significantly benefited from the accelerated progression of Additive Manufacturing (AM) technologies [29]. The identification of the enhanced heat transfer capabilities of high roughness cooling channels in liquid rocket engine regenerative cooling systems concurring with the technological advancements in the engineering field of Additive Manufacturing (AM), resulted in

the fabrication of metallic components for high-heat flux aerospace applications using AM processes. The effect of surface roughness on the flow-field development and the heat transfer characteristics in an AM minichannel was investigated in [30]. The authors were able to identify enhanced heat transfer capabilities of the high roughness channels fabricated using additive manufacturing technologies comparing to smooth channels. The authors further investigated the roughness effects in AM microchannels of small characteristic dimensions, through the derivation of formulations correlating the surface roughness effect on the pressure loss and heat transfer with physical roughness measurements [31]. The utilisation of surfaces fabricated by additive manufacturing techniques for cooling purposes of high-heat flux aerospace applications is a direct consequence of the exhibition of the AM cooling channels enhanced heat transfer capabilities. The effects of the employed Additive Manufacturing (AM) process on the surface roughness and heat transfer capabilities of cooling channels of various geometric characteristics are discussed in [32–34]. Heat transfer predictions in turbulent flows in AM channels of high roughness are also available in the literature both from a numerical [35] and experimental [36] point of view.

Current trends in the field of Additive Manufacturing (AM) suggest the utilisation of copper-based alloys for high-heat flux aerospace applications, as a result of the enhanced mechanical properties and thermal conductivity of the alloys [37]. An ideal copper alloy candidate for the fabrication of metallic components including regenerative cooling systems of combustion chambers is the GRCo-42 copper alloy [29]. The GRCo-42 copper-based alloy is composed of Cu-4 at.%Nb and Fe, O, Al and Si in smaller concentrations. Experimental measurements on the thermophysical and mechanical properties of GRCo-42 are available in the literature [29,38]. A comprehensive review of various additive manufacturing techniques for the fabrication of copper-chromium-niobium alloys can be found in [39]. The combination of the important engineering growth of AM processes and the benefits of copper-based alloys on the solid material properties to be able to withstand significant amounts of heat transfer, led to the development of the novel high-heat flux propulsion concepts such as the DemoP1 aerospike engine demonstrator, a 20 [kN] thrust LOx/LNG aerospike engine demonstrator carried out by Pangea Aerospace [40]. The inspiration behind the development of the DemoP1 aerospike engine demonstrator originated in highlighting the key features of the next generation booster-class rocket engines, such as reusability and the integration of dual regenerative cooling systems using the cryogenic propellants of the liquid rocket engine. An important metallic component of the DemoP1 aerospike engine demonstrator is the dual regenerative cooling system of the rocket engine, which is based on counterflowing cryogenic liquid oxygen in AM cooling channels from the base up to the injector head of the engine and through the central plug, in addition to cooling the external housing of the rocket engine by flowing liquid natural gas. In this way, the increased thermal load demands encountered across the aerospike engine and more significantly, at the throat region of the rocket engine, are satisfied. The AM fabrication of the engine demonstrator is based on the Selective Laser Melting (SLM) manufacturing technique, using the GRCo-42 copper-based alloy. As discussed, the high, non-uniform surface roughness inherited from the AM process is expected to enhance the heat transfer capabilities of the dual regenerative cooling system, however larger pressure drop values are expected in the AM cooling channels of the demonstrator. Details on the structural development, fabrication and the full-scale single-injector hot-fire testing campaign of the DemoP1 aerospike engine demonstrator are discussed in [41,42]. With respect to the cooling performance of the dual regenerative cooling system of the DemoP1 liquid rocket engine, a numerical solution of the cryogenic liquid oxygen flow in the AM cooling channel of the demonstrator is reported in [43]. In their work, the authors proceed in a numerical investigation of different variations of the two-equation $k - \omega$ turbulence model to accurately predict the

flow-field development and heat transfer characteristics of the cryogenic propellant flow in the AM cooling channel of the demonstrator. The development of the DemoP1 aerospike engine demonstrator is a characteristic example of how the advantageous features from the employment of additive manufacturing techniques enhance the cooling capabilities of high-heat flux propulsion concepts. A detailed discussion on the research activities for the development of the DemoP1 aerospike engine demonstrator can be found in [40].

In the current work, a numerical characterisation of the cryogenic liquid oxygen flow in the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator is presented. For this purpose, various parameters required for the determination of the heat transfer and pressure drop characteristics of the cryogenic propellant flow in the microfluidic cooling channel are determined and discussed. A peculiar Nusselt number correlation for the description of the heat transfer behaviour in the AM cooling channel is also introduced. As exhibited from the investigations available in the literature, the behaviour of a cryogenic coolant in an AM microfluidic cooling channel of an aerospike engine has not yet been comprehended. Following the ever-growing technological developments in the field of high-heat flux aerospace applications, it is of uttermost importance to characterise the propellant behaviour in rocket engine cooling channels. The work presented in the current study aims to fill this literature gap, by providing a preliminary yet comprehensive characterisation of the coolant flow in an AM microfluidic cooling channel of the DemoP1 aerospike engine demonstrator. Apart from providing a review of the heat transfer and pressure drop characteristics of the cryogenic coolant flow in the AM cooling channel of the aerospike engine demonstrator, the results presented in the current work aim at contributing to overcoming the thermal management limitations arising in high-heat flux aerospace applications.

The structure of the current work is as follows. In Section 2, the numerical methods for the solution of the cryogenic liquid oxygen flow in the AM cooling channel of the DemoP1 aerospike engine demonstrator are presented. In addition to a discussion on the governing equations and the turbulence model employed for the solution of the cryogenic coolant flow, the three-dimensional geometric configuration of the AM cooling channel is also reported. The methodology section is concluded by discussing the numerical settings on the commercial CFD package and the derivation of the thermal boundary condition applied on the heated bottom (basement) wall boundary of the microfluidic cooling channel of the liquid rocket engine demonstrator. In Section 3, computational results in comparison with available experimental measurements obtained from the hot-fire testing campaign of the DemoP1 aerospike engine demonstrator are discussed. Furthermore to the determination of the cryogenic coolant primitive variables development across the AM cooling channel, the variation of the thermophysical properties of the cryogenic liquid oxygen is also investigated. Ultimately, a peculiar Nusselt number correlation is derived for the characterisation of the heat transfer behaviour of the cryogenic coolant in the rectangular cross-section cooling channel of the DemoP1 aerospike engine demonstrator. In Section 4, the conclusions of the numerical characterisation of the cryogenic liquid oxygen flow in the AM cooling channel presented in this work are briefly summarised.

2. Methodology

In this section, the numerical methods employed for the solution of the governing equations required for the description of the cryogenic coolant flow-field development in the Additively Manufactured (AM) microfluidic cooling channel of the DemoP1 aerospike engine demonstrator are presented. Following the exhibition of the geometric configuration of the three-dimensional, microfluidic curved cooling channel of variable, rectangular cross-section, a methodology available in the literature for the estimation of the roughness height of the AM cooling channel wall boundaries is reported. Subsequently, the

numerical settings for the implementation of the required simulations in the commercial Computational Fluid Dynamics (CDF) package are discussed. In the last part of this section, the thermal boundary condition at the bottom (basement) wall of the AM cooling channel of the liquid rocket engine demonstrator is derived.

2.1. Numerical methods and governing equations

In the case of cryogenic coolant flows characterised by turbulent phenomena and high Reynolds numbers, the numerical solution of the system of governing equations consisting of the mass conservation (continuity) and the momentum equations is required [44]. In the present numerical investigation, the Favre-Averaged Navier–Stokes (FANS) equations are employed for the numerical solution of the steady-state, compressible turbulent flow of the liquid oxygen cryogenic coolant in the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator. The FANS equations consisting of the mass continuity (conservation), momentum and energy equations are written in Cartesian index notation as follows [45]

$$\frac{\partial}{\partial x_i} (\rho u_i) = 0, \quad (1)$$

$$\frac{\partial}{\partial x_i} (\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \right] + \frac{\partial}{\partial x_j} (-\rho \overline{u'_i u'_j}), \quad (2)$$

$$\frac{\partial}{\partial x_j} [u_i (\rho E + p)] = \frac{\partial}{\partial x_j} \left[\left(\lambda + \frac{c_p \mu_t}{Pr_t} \right) \frac{\partial T}{\partial x_j} + u_i (\tau_{ij})_{eff} \right], \quad (3)$$

where $i, j = 1, 2, 3$ refers to the three Cartesian coordinate directions, u_i is the velocity component in the corresponding direction, ρ is the variable-density of the fluid, P is the pressure, μ the fluid dynamic viscosity, δ_{ij} the Kronecker delta and E is the total energy, defined as $E = c_p T - \frac{p}{\rho} + \frac{u^2}{2}$. In the energy equation of the system of governing equations reported in Eq. (3), λ refers to the fluid thermal conductivity, c_p is the fluid specific heat capacity at constant pressure, μ_t is the turbulent (eddy) dynamic viscosity of the fluid, Pr_t is the turbulent Prandtl number and T is the fluid static temperature. The tensor $(\tau_{ij})_{eff}$ appearing in Eq. (3), indicates the viscous stress tensor defined as

$$(\tau_{ij})_{eff} = \mu_{eff} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu_{eff} \frac{\partial u_k}{\partial x_k} \delta_{ij}, \quad (4)$$

for $i, j = 1, 2, 3$ and $j \neq i$. In the case of the FANS equations employed in the current work, the physical quantities appearing in the governing equations represent the density-weighted averaged values. Note that in the present numerical investigation the computed average Mach number is 0.31. However, the employment of the FANS equations for the solution of the compressible coolant flow is justified since the Mach number of the coolant flow reaches values up to 1.24, especially at the throat region of the Additively Manufactured (AM) cooling channel. More details on the determination of the flow field development across the cooling channel of the DemoP1 aerospike engine demonstrator are reported in Section 3. Furthermore, in the current work for the characterisation of the cryogenic LOx coolant flow in the AM cooling channel, the two-equation $k-\omega$ Shear Stress Transport (SST) turbulence model is employed. The two-equation $k-\omega$ SST turbulence model has been previously employed for the solution of internal, turbulent flows of cryogenic coolants in rough channels, with rather promising results [22,43].

2.2. Geometric configuration of cryogenic coolant flow cooling channel

In the present numerical investigation, the cryogenic liquid oxygen flow is bounded in an Additively Manufactured (AM) cooling channel, as part of the dual regenerative cooling system of the DemoP1 aerospike engine demonstrator designed by Pangea Aerospace. The geometric configuration of interest is a three-dimensional, microfluidic curved channel of variable, rectangular cross-section [40]. At the

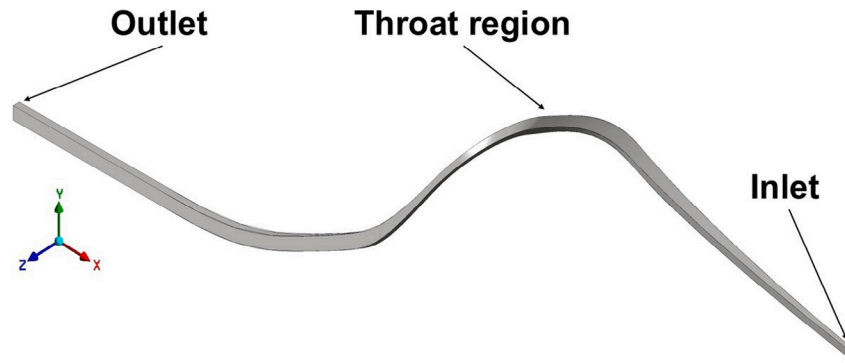


Fig. 1. Three-dimensional geometric configuration of Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator.

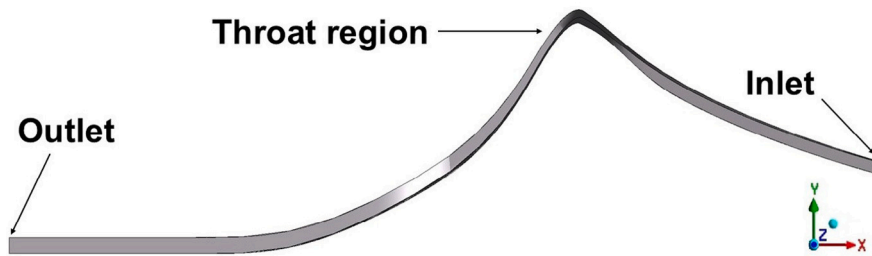


Fig. 2. Projection of geometric configuration of Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator in XY coordinate plane.

Table 1

Coordinate and region characterisation of different cross-sections across longitudinal coordinate of coolant side.

Number of cross-section	Channel region	Coordinate [m]	D_h [mm]	A [μm]
1	Outlet	0	2.677	8.091
2	Interim	0.02	2.677	8.091
3	Interim	0.04	2.677	8.090
4	Interim	0.06	2.672	8.177
5	Interim	0.08	2.661	7.928
6	Interim	0.10	2.744	8.163
7	Throat exit	0.12	2.404	7.456
8	Throat	0.14	1.671	4.523
9	Throat beginning	0.16	3.106	9.884
10	Interim	0.18	2.788	7.975
11	Interim	0.20	2.124	5.078
12	Inlet	0.22	1.463	2.986

throat region of the cooling channel, a very strong curvature is exhibited, contrary to the remaining sections of the microfluidic channel. The three-dimensional, geometric configuration of the cryogenic liquid oxygen cooling channel of the demonstrator can be seen in Figs. 1 and 2, fabricated by means of additive manufacturing as discussed in Section 1.

For the implementation and performance of the required numerical simulations and post-processing analysis of the computational results for the cryogenic liquid oxygen flow in the Additively Manufactured (AM) cooling channel, averaged measurements on different variables of interest are obtained from twelve different cross-sections. The investigated cross-sections are uniformly distributed across the longitudinal coordinate of the AM cooling channel. A summary of the longitudinal coordinate location and the corresponding cooling channel region that each cross-section has been placed, in addition to the estimated hydraulic diameter and area of each channel cross-section, is reported in Table 1.

Note that the inlet section of the Additively Manufactured (AM) cooling channel is represented at the right-hand side, whilst the outlet channel section at the left-hand side of the figures exhibited in the

present study, at the longitudinal coordinate, $z = 0.22$ [m] and $z = 0$ [m], respectively. Initially, it is important to analyse the geometric configuration of the AM cooling channel of the engine demonstrator, based on Fig. 3. The variation of the hydraulic diameter variable across the cooling channel of the DemoP1 aerospike engine demonstrator against the longitudinal coordinate of the cooling channel is depicted in Fig. 3. For the estimation of the hydraulic diameter D_h for the cryogenic coolant flow through the variable, rectangular cross-section AM cooling channel, the following formulation is employed, $D_h = 2HW/(H + W)$, where H is the height and W the width of the corresponding rectangular cross-section. Similarly, the variation of the cross-section area against the longitudinal coordinate of the cooling channel is exhibited in Fig. 3, where the cross-section area of the three-dimensional, microfluidic curved cooling channel is estimated as $A = H \cdot W$.

The throat region of the cryogenic liquid oxygen Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator can be seen around the longitudinal coordinate of $z = 0.14$ [m] in Fig. 3. The variation of the hydraulic diameter and the cross-section area across the longitudinal coordinate of the AM cooling channel is evident. More specifically, both geometric variables exhibit an increment up to the beginning of the throat region of the channel at $z = 0.16$ [m]. Inside the throat region area, the fluidic width noticeably decreases up to half the magnitude of the corresponding geometric variable at the beginning of the throat. There is a very important reason behind this design consideration for the reduction of the fluidic width available at the throat region of the cryogenic liquid oxygen AM cooling channel. This design consideration is explained on the basis of enhancing the cooling capabilities of the AM cooling channel, to withstand the increased thermal load applied at the throat of the cooling channel from the hot-gas side of the DemoP1 aerospike engine demonstrator [40]. In a sense, a smaller available fluidic width results in an increased coolant velocity counterflowing within the throat region and therefore, enhanced cooling capabilities at the most challenging section of the AM cooling channel. Following the determination of the geometric features of the three-dimensional, microfluidic curved channel of variable, rectangular cross-section, the numerical procedures

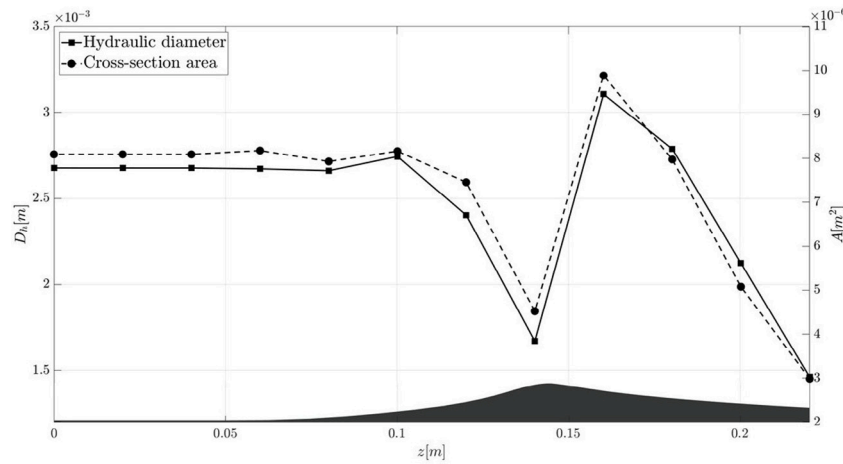


Fig. 3. Hydraulic diameter and cross-section area at different cross-sections across longitudinal coordinate of cryogenic coolant side.

for the estimation of the roughness height at the wall boundaries of the AM cooling channel will be presented in the next section.

In the subsequent sections, the numerical procedure details for the performance of the required CFD simulations and the mathematical process for the derivation of the thermal boundary condition imposed on the heated bottom (basement) wall boundary of the Additively Manufactured (AM) microfluidic cooling channel of the DemoP1 aerospike engine demonstrator are presented.

2.3. Numerical procedures details

For the numerical solution of the cryogenic liquid oxygen (LOx) in the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator, specific numerical activities have been performed. As discussed and exhibited in Section 2.2, the geometric configuration of interest is a three-dimensional curved channel of rectangular, variable cross-section for the reduction of the fluidic width at the throat section of the channel and the overall satisfaction of the increased heat transfer demands of the AM cooling channel [40]. The three-dimensional model investigated consists of the inlet and outlet section, in addition to the surrounding wall boundaries bounding the cryogenic propellant flow in the AM channel. The thermal load from the hot-gas side of the DemoP1 aerospike engine demonstrator is imposed as a boundary condition on the geometric configuration through the bottom (basement) wall of the microfluidic cooling channel. The remaining wall boundaries are considered adiabatic and therefore, no heat flux is applied.

The three-dimensional computational fluid dynamics (CFD) approach implemented in the current investigation is based on an implicit, density-based method for the numerical solution of the steady-state, Favre-Averaged Navier–Stokes (FANS) equations. As discussed in Section 2.1, the two-equation $k-\omega$ Shear Stress Transport (SST) turbulence model is employed for the turbulence closure problem. The numerical simulation performed in the current investigation is based on the continuum approach for the description of the liquid oxygen flow in the AM cooling channel. The thermophysical properties of the liquid oxygen working fluid are determined as follows: density is estimated based on the ideal-gas law, specific heat capacity at constant pressure using a fifth-order piecewise polynomial varying with respect to the static temperature, the fluid thermal conductivity is computed by utilising the kinetic theory and for the definition of the dynamic viscosity of the fluid, Sutherland's law is employed. The solid material properties of GRCop-42 copper-based alloy are constant with temperature and are estimated in the standard room temperature, 298.2 [K], as: $\rho_w = 8777.39$ [kgm⁻³], $c_{p,w} = 383.84$ [Jkg⁻¹K⁻¹] and $k_w = 381.12$ [Wm⁻¹K⁻¹]. The numerical discretisation of the governing and transport equations is

performed as follows: a Roe Approximate Riemann Solver (ARS) [46] is selected for the discretisation of the convective fluxes and second-order accurate upwind schemes are employed for pressure, momentum, energy and the transport quantities of the employed turbulence model. With the exception of the convergence criterion for the energy residuals set equal to 10^{-12} , the convergence criterion for the remaining residuals is set equal to 10^{-8} . Similarly to the fluid reference values being computed from the inlet of the AM cooling channel of the engine demonstrator, the solution is initialised using the standard initialisation method from the inlet section, in a reference frame relative to the cell zone.

The experimental data obtained from the hot-flow testing campaign of the DemoP1 aerospike engine demonstrator are imposed in the form of boundary conditions on the commercial CFD package for the numerical solution in the Additive Manufacturing (AM) cooling channel. Initially, the coolant flow is fully-developed. At the inlet section of the microfluidic cooling channel, a fixed mass flow rate equal to $\dot{m} = 0.08$ [kgs⁻¹] and a uniform temperature profile $T = T_{in} = 107.4$ [K] are imposed. At the outlet section of the AM cooling channel, a Dirichlet-type pressure boundary condition is employed equal to the experimentally measured value $P = P_{out} = 57.09$ [bar]. Note that the accuracy of the pressure sensors utilised during the experimental campaign of the DemoP1 aerospike engine demonstrator is reported as ± 0.8 [bar] and the accuracy of the temperature sensors as ± 7 [K]. At the wall boundaries of the computational domain, no-slip boundary conditions are imposed for the velocity components in all three spatial directions. In addition, for the modelling of the surface roughness, the standard roughness option on the commercial CFD package was selected. Based on a comprehensive review for the determination of the equivalent sand-grain roughness height reported in the appendix, the roughness height of the investigated rough, microfluidic channel flow is determined as $k_s = 49.17$ [μ m] and is equal to the equivalent sand-grain roughness height obtained from the optical profilometry measurements and the resulted statistical surface roughness parameters of the metallic, AM sample of the demonstrator. The roughness constant is set equal to 0.75 to account for the non-uniform distribution of the rough elements induced by the AM process. As discussed, the heat load from the hot-gas side of the DemoP1 aerospike engine demonstrator is applied on the bottom (basement) wall boundary of the AM cooling channel and the heat flux at the top and lateral walls is set equal to zero, as the remaining wall boundaries of the computational domain are assumed to be adiabatic. In the present numerical investigation, a total number of $5 \cdot 10^4$ iterations were performed for the numerical characterisation of the cryogenic liquid oxygen flow in the AM cooling channel of the DemoP1 aerospike engine demonstrator.

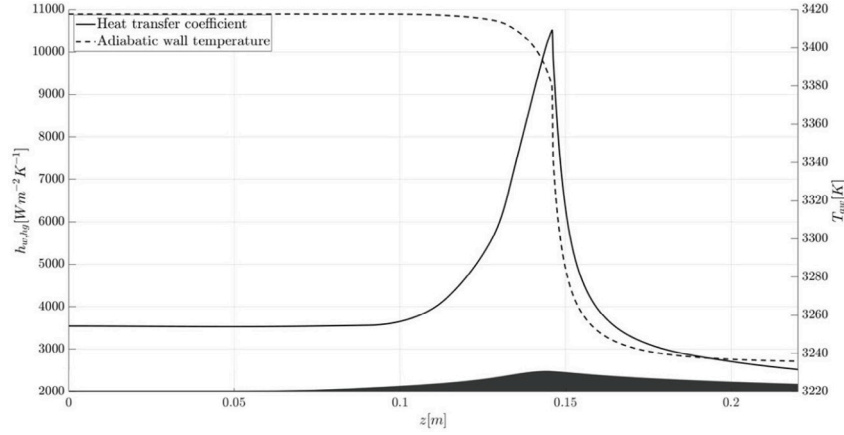


Fig. 4. Hot-gas side convective heat transfer coefficient and adiabatic wall temperature across longitudinal coordinate of cryogenic coolant side.

2.4. Thermal boundary condition derivation

For the derivation of the thermal boundary condition at the bottom (basement) wall of the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator, specific mathematical operations based on computations on the hot-gas side of the demonstrator were performed. In the design phase of the liquid rocket engine demonstrator, particular attention has been brought to the throat region of the engine with respect to the increased heat fluxes applied at the specific area. Throughout the estimations performed on the hot-gas side of the investigated liquid rocket engine, it is a usual approach to account for the convection and the radiation phenomena from the hot-gas side to the solid walls. The determination of the heat transfer rate from the hot-gas side of the engine demonstrator to the solid material wall medium requires the input of the adiabatic wall temperature of the gas, the hot-gas side convective heat transfer coefficient and the hot-gas side wall temperature. The formulation for the estimation of the convective heat transfer coefficient at the hot-gas side of the engine demonstrator is given as [47]

$$q_{w,hg} = h_{w,hg} (T_{aw} - T_{w,hg}), \quad (5)$$

where $q_{w,hg}$ is the heat transfer rate applied from the hot-gas side to the metal wall boundary of the Additively Manufactured (AM) cooling channel, $h_{w,hg}$ is the convective heat transfer coefficient, T_{aw} is the adiabatic wall temperature of the gas and $T_{w,hg}$ is the hot-gas side local chamber wall temperature. The hot-gas side wall temperature is assumed to be uniform and equal to $T_{w,hg} = 800$ [K]. The convective heat transfer coefficient and the adiabatic wall temperature from the hot-gas side of the DemoP1 aerospike engine demonstrator across the longitudinal coordinate of the metallic walls of the AM cooling channel are reported in Fig. 4.

In Fig. 4, increased values of the hot-gas side convective heat transfer coefficient are exhibited at the throat region of the Additively Manufactured (AM) cooling channel, around the longitudinal coordinate of $z = 0.14$ [m]. More specifically, following the computations performed at the hot-gas side of the DemoP1 aerospike engine demonstrator, it is shown that the hot-gas side convective heat transfer coefficient appears to increase in the region from the inlet up to the beginning of the throat region. The maximum value of the hot-gas side convective heat transfer coefficient is located inside the throat region and is approximately $10,500$ [$\text{kWm}^{-2}\text{K}^{-1}$]. From the middle up to the exit of the throat region, the hot-gas side convective heat transfer coefficient decreases, until it reaches a value of roughly 3600 [$\text{kWm}^{-2}\text{K}^{-1}$]. The values for the hot-gas side convective heat transfer coefficient stabilise around this value for the region covering the exit of the throat up to the outlet section of the AM cooling channel of the DemoP1 aerospike engine demonstrator. The global minimum value

of the hot-gas side convective heat transfer coefficient is exhibited at roughly 2500 [$\text{kWm}^{-2}\text{K}^{-1}$]. The adiabatic wall temperature of the combustion gas across the longitudinal coordinate of the AM cooling channel walls of the liquid rocket engine demonstrator is exhibited in Fig. 4. In the case of hot-gas side adiabatic wall temperature, an adverse temperature gradient is observed at the throat region of the DemoP1 aerospike engine demonstrator. More specifically, the hot-gas side adiabatic wall temperature exhibits a negligible increment from the inlet section of the AM cooling channel up to the beginning of the throat region, and is roughly constant and equal to 3417 [K] from the exit of the throat region up to the outlet section of the cooling channel. However, the hot-gas side adiabatic wall temperature gradient observed at the throat region is adverse, as the adiabatic temperature is approximately 3240 [K] at the beginning and 3417 [K] at the exit of the engine throat.

Following the determination of the convective heat transfer coefficient and the adiabatic wall temperature in Fig. 4 at the hot-gas side of the DemoP1 aerospike engine demonstrator, the heat transfer rate applied from the hot-gas side to the bottom (basement) wall boundary of the Additively Manufactured (AM) cooling channel can be estimated based on Eq. (5). Subsequently to the estimation of the convective heat transfer coefficient and heat transfer rate from the hot-gas side to the GRCop-42 solid material wall of the Additively Manufactured (AM) cooling channel, the solution of the Fourier equation for the one-dimensional heat conduction is required. Note that dual regenerative cooling systems for thrust chambers of liquid rocket engines are characterised by an exchange of heat flow between the gases at the hot-gas side of the rocket engine and the counterflowing cryogenic propellant at the coolant-side of the cooling channel. The steady-state correlation for the balance of the heat fluxes from the hot-gas side to the wall material, the wall conduction, and the heat flux applied from the wall material to the coolant-side is described as [47]

$$h_{w,hg} (T_{aw} - T_{w,hg}) = q = \left(\frac{k_w}{t_w} \right) (T_{w,hg} - T_{w,c}), \quad (6)$$

where q is the heat transfer rate, k_w is the thermal conductivity of the wall material of the Additively Manufactured (AM) cooling channel, t_w is the width of the solid material wall equal to 1 [mm] and $T_{w,c}$ is the coolant-side wall temperature to be determined and imposed as a thermal boundary condition at the bottom (basement) wall of the cooling channel. Assuming the hot-gas side wall temperature is uniform, the solution of Fourier's equation for the one-dimensional heat conduction through the AM cooling channel wall results in the coolant-side wall temperature profile exhibited in Fig. 5. The integration of the estimated coolant-side wall temperature profile into the commercial CFD package and its utilisation as the thermal boundary condition for the bottom (basement) wall of the Additively Manufactured (AM)

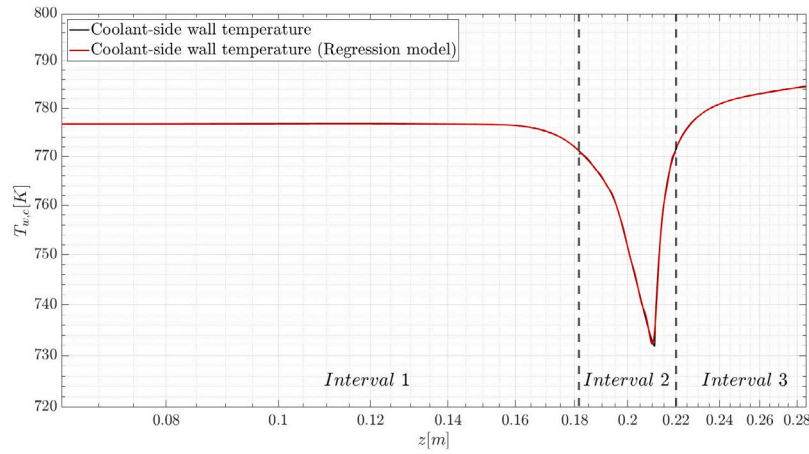


Fig. 5. Coolant-side wall temperature profile and regression model for its curve fit.

cooling channel of the DemoP1 aerospike engine demonstrator requires the performance of specific statistical processes. A regression analysis performed allows for the inference of a casual correlation from the dataset of the distinct coolant-side wall temperature values and the longitudinal coordinate of the cooling channel. For the accurate determination of appropriate correlations for the coolant-side wall temperature with respect to the cooling channel coordinate, the resulted temperature profile in Fig. 5 is split into three distinct, spatial intervals. Different regression models are employed in each interval to properly fit the resulting curve of the coolant-side wall temperature profile at the heated bottom (basement) wall of the AM cooling channel of the DemoP1 aerospike engine demonstrator. The curve fitting and the extraction of the regression model correlations is performed on the Curve Fitter toolbox of MATLAB R2022a [48].

The coolant-side wall temperature at the bottom (basement) wall of the cooling channel at the first spatial interval ranging from 0.065 [m] to 0.182 [m] is fitted through the employment of a fourth-order Fourier regression model. The goodness of fit characterising the employed fourth-order Fourier regression model for the curve fitting of the coolant-side wall temperature profile at the first spatial interval is described from an R-squared value of 0.9999 and a root-mean-square error equal to 0.01277. The second spatial interval ranging from 0.182 [m] up to 0.22 [m] includes the throat region of the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator and the accurate fit of the resulted coolant-side wall temperature profile requires a higher-order regression model. Therefore, for the second interval of the coolant-side wall temperature profile at the bottom (basement) wall of the AM cooling channel, an eighth-order Fourier regression model is employed. In this case, the regression model goodness of fit is characterised by the statistical metrics $R^2 = 0.9981$ and a root-mean-square error value of $RMSE = 0.5574$. Lastly, a second-order exponential regression model is employed for the third spatial interval of the cooling channel longitudinal coordinates ranging from 0.22 [m] to 0.285 [m], characterised by the statistical metrics of an R-squared value equal to 1 and a root-mean-square error of roughly 0. The estimated coolant-side wall temperature profile at the heated bottom (basement) wall boundary of the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator, in addition to the fit curve resulted from the employment of the different regression models in the corresponding spatial intervals is exhibited in Fig. 5. The resulting casual correlations are ultimately utilised for the construction of a User-Defined Function (UDF) and its integration into the commercial CFD package, for the determination of the imposed thermal boundary condition at the heated bottom (basement) wall of the AM cooling channel of the aerospike engine demonstrator. The

deduction of the thermal boundary condition for the heated bottom (basement) wall of the cryogenic liquid oxygen flow concludes the establishment of the boundary conditions for all computational domain boundaries of the microfluidic cooling channel, including the surrounding wall boundaries, in addition to the channel inlet and outlet sections. In the subsequent section, a comprehensive analysis of the results of the CFD simulation for the numerical characterisation of the cryogenic liquid oxygen in the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator is presented.

3. Results and discussion

In this section, the analysis for the numerical characterisation of the cryogenic liquid oxygen flow in the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator is presented. Initially, a grid independence study is performed for the determination of an appropriate grid size for the required numerical simulation. Subsequently, the characterisation of the cryogenic coolant primitive variables of temperature, pressure, velocity and density is reported, in addition to a discussion on the development of the thermo-physical properties of the cryogenic liquid oxygen across the microfluidic cooling channel. Finally, a peculiar Nusselt number correlation is derived for the description of the cryogenic coolant thermal behaviour in the asymmetrically heated, rectangular cross-section, microfluidic cooling channel of the liquid rocket engine demonstrator.

3.1. Grid independence study

A grid independence study is carried out for the determination of an appropriate grid size for the CFD simulation required for the numerical characterisation of the cryogenic liquid oxygen flow in the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator. The total number of cells for the coarse, intermediate and fine grid examined is reported in Table 2. The reason for selecting the number of cells is the accurate results that the numerical simulations produced, comparing to the experimental data available from the hot-fire testing campaign of the DemoP1 aerospike engine demonstrator. The investigated test case considers the numerical simulation employing the two-equation $k - \omega$ SST turbulence model [49] under the guidelines on the commercial CFD package reported in Section 2.3.

The metric of interest for the determination of an appropriate grid size is the temperature profile at the outlet section of the cryogenic liquid oxygen Additively Manufactured (AM) cooling channel at the midline from the heated bottom (basement) wall up to the adiabatic top wall boundary. In Fig. 6, minor deviations are observed between the

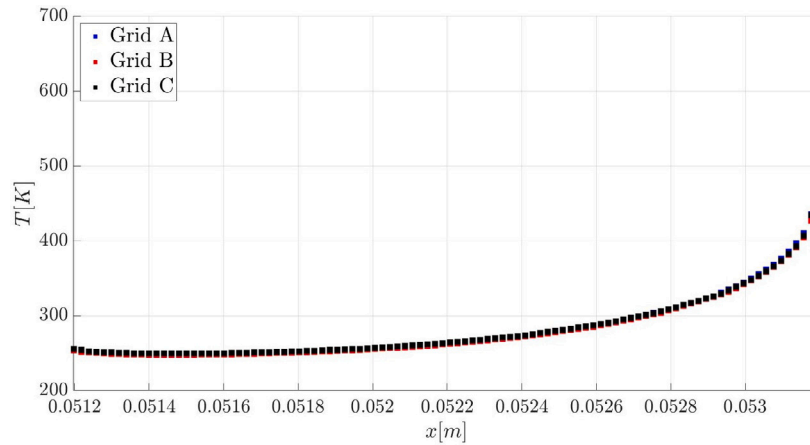


Fig. 6. Grid sensitivity analysis for the cryogenic coolant temperature profile at the bottom (basement)-top wall midline of the outlet section of the cryogenic cooling channel.

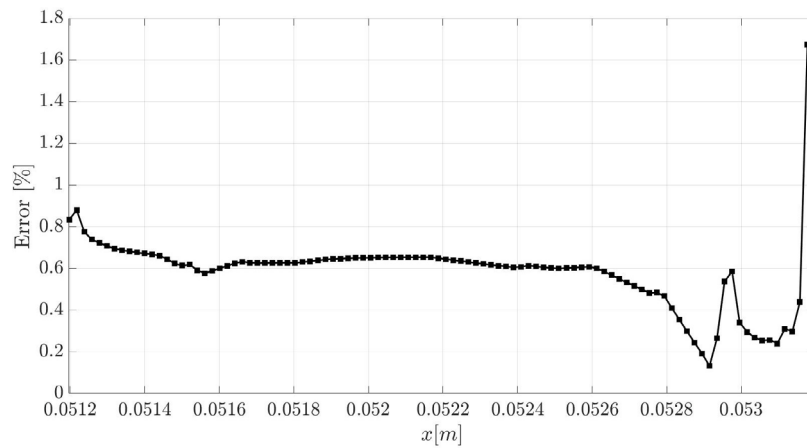


Fig. 7. Percentage error across basement-top wall midline of the outlet section of the AM cooling channel between simulations employing Grid B (intermediate) and Grid C (fine).

Table 2

Total number of cells for the investigated grids.

	Number of cells
Grid A (coarse)	0.87M
Grid B (intermediate)	1.3M
Grid C (fine)	2.6M

temperature profiles obtained for the coarse, intermediate and fine grid simulations investigated. The displacement of Grid A (coarse) compared to Grid B (intermediate) and Grid C (fine) is explained on the basis of the coarseness of the grid. The mean error percentage estimated between the cryogenic coolant temperature values obtained from the numerical solution employing Grid A (coarse) and Grid C (fine) is 0.46%. The mean percentage deviation reported between the numerical solution obtained by employing Grid B (intermediate) and Grid C (fine) is computed as 0.58%.

The percentage error between the temperature profiles resulted from the performed Computational Fluid Dynamics (CFD) simulations employing the intermediate and the fine grids across the midline is also computed. As reported in Fig. 7, the percentage error between the CFD simulations is well below 1%, excluding a point where the percentage deviation reaches up to approximately 1.7%. The grid independence study carried out indicates the employment of Grid C (fine) for the implementation of the simulation required for the numerical characterisation of the cryogenic coolant in the AM microfluidic cooling channel of the liquid rocket engine demonstrator.

3.2. Characterisation of cryogenic coolant primitive variables

The numerical solution for the cryogenic liquid oxygen flow in the Additively Manufactured (AM) microfluidic cooling channel of the DemoP1 aerospike engine demonstrator is compared against the experimentally measured average coolant temperature at the outlet section of the AM cooling channel. Based on the experimental data obtained from the hot-fire testing campaign of the liquid rocket engine demonstrator, the experimentally measured average temperature value at the outlet section of the AM cooling channel is equal to $T_{out} = 305.07$ [K]. As discussed, the numerical setup details for the implementation of the required Computational Fluid Dynamics (CFD) simulation, including the thermophysical properties of the cryogenic coolant (liquid oxygen) and the solid (GRCop-42 copper-based alloy) material, the numerical settings for the commercial CFD package, the surface roughness at the wall boundaries and the boundary conditions for the numerical solution of the LOx flow in the AM cooling channel are reported in Section 2.

The present investigation performed for the numerical characterisation of the cryogenic coolant in the Additively Manufactured (AM) liquid rocket engine cooling channel relies on the characterisation of the primitive variables of temperature, pressure, velocity and density of the cryogenic liquid oxygen, as it counterflows from the base to the injector plate of the DemoP1 aerospike engine demonstrator. Initially, the average bulk temperature of the cryogenic coolant in the different cross-sections of the microfluidic cooling channel is exhibited in Fig. 8. As shown in Fig. 8, the liquid oxygen coolant enters the AM cooling channel at a cryogenic temperature of $T_{in} = 107.4$ [K].

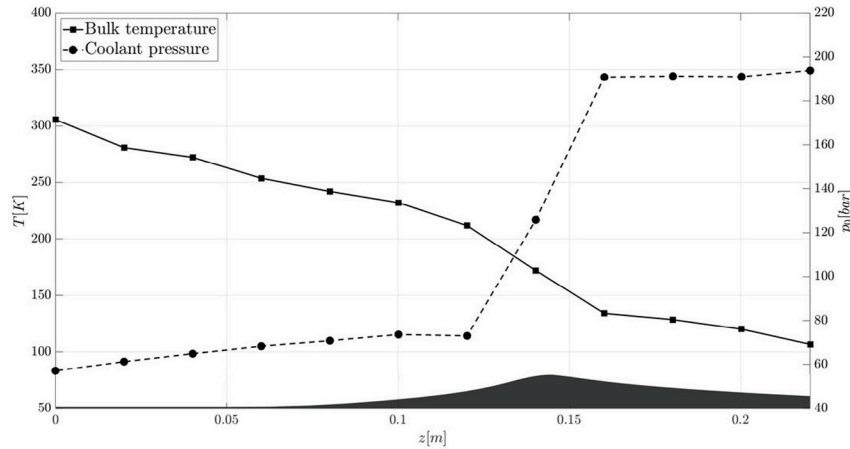


Fig. 8. Average bulk temperature and coolant pressure at different cross-sections across longitudinal coordinate of cryogenic coolant side.

Note that, as discussed in Section 2.3, the average coolant temperature in the form of a uniform temperature profile has been imposed as a boundary condition at the inlet section of the AM cooling channel, based on the experimentally measured value obtained during the hot-fire testing campaign of the DemoP1 aerospike engine demonstrator. As the cryogenic coolant counterflows inside the AM microfluidic cooling channel of the liquid rocket engine demonstrator, a non-uniform heat load is applied from the hot-gas side of the engine demonstrator on the bottom (basement) wall boundary of the AM cooling channel. As a result, a temperature gain of the cryogenic propellant is observed in Fig. 8 across the range of the longitudinal coordinate of the coolant side. In comparison with the remaining sections of the AM cooling channel where a gradual bulk temperature gain is observed, the bulk temperature gradient at the throat region of the microfluidic cooling channel is rapid.

In the case where large temperature variations are observed as the cryogenic coolant counterflows through the Additively Manufactured (AM) microfluidic cooling channel from the base of liquid rocket engine to the injector head, it is important to quantify the bulk temperature gradient in the different regions of the cooling channel. The AM cooling channel of the DemoP1 aerospike engine demonstrator is therefore divided into three distinct regions: the region from the channel inlet section up to the beginning of the throat region, the throat region of the cooling channel and finally, the region from the exit of the throat up to the outlet section of the microfluidic cooling channel. As indicated in Fig. 8, the average gradient of the cryogenic coolant temperature at the throat region is approximately an order of magnitude larger comparing to the remaining sections of the AM cooling channel. Furthermore, the lowest average temperature gradient is observed in the region between the inlet section of the AM cooling channel and the cross-section located at the beginning of the throat region. More specifically, the average temperature gradient value at the region prior to the beginning of the throat region is estimated as $455.44 \text{ [Km}^{-1}\text{]}$, the average temperature gradient at the throat region is $1630.76 \text{ [Km}^{-1}\text{]}$ and the average temperature gradient at the remaining section of the AM cooling channel is computed as $734.01 \text{ [Km}^{-1}\text{]}$. The large deviations in the average gradient values between the throat region and the remaining sections of the microfluidic cooling channel provide further evidence on the numerical modelling complexities at the throat region of the DemoP1 aerospike engine demonstrator cooling channel. However, as discussed, this adverse temperature gradient is expected considering the three-dimensional geometric configuration of the engine demonstrator and the strong curvature at the throat region, in addition to the larger heat load applied at the throat region from the hot-gas side of the liquid

rocket engine to the cryogenic coolant-side. This phenomenon is a direct implication of the design considerations on the AM cooling channel, especially encountered in high-heat flux, high-pressure aerospace applications such as the DemoP1 aerospike engine demonstrator [40]. The bulk temperature variation across different variable, rectangular cross-sections of the three-dimensional, microfluidic cooling channel of the DemoP1 engine demonstrator is exhibited in Fig. 9. As shown in Fig. 9, excluding the inlet section of the microfluidic cooling channel where a fixed value for the bulk temperature has been imposed as equal to $T_{in} = 107.4 \text{ [K]}$, the largest bulk temperatures at each cross-section are observed adjacent to the asymmetrically heated, bottom wall boundary of the AM cooling channel. Note that in Fig. 9 a three-dimensional representation of the AM cooling channel is exhibited. However, for clarity purposes, the investigated cross-sections across the longitudinal coordinate of the microfluidic cooling channel are depicted in an XY coordinate plane.

Subsequent to the quantification of the average temperature gradient across the longitudinal coordinate of the Additively Manufactured (AM) microfluidic cooling channel, the comparison of the numerically estimated average bulk temperature of the cryogenic coolant at the channel outlet section with the experimental measurements obtained from the hot-fire testing campaign of the DemoP1 aerospike engine demonstrator is implemented. As discussed, the experimental data for the cryogenic coolant temperature at the outlet section of the microfluidic cooling channel indicate a value of $T_{out} = 305.07 \text{ [K]}$. Based on the performed numerical simulation, the average temperature of the cryogenic coolant at the outlet section of the AM cooling channel is estimated as 302.84 [K] . Therefore, the percentage deviation between the numerical solution and the experimental data of the average coolant temperature at the channel outlet section obtained from the hot-fire testing campaign of the liquid rocket engine demonstrator is computed as 0.73% , which is within an acceptable range for high-heat flux, high-pressure aerospace applications. Note that numerical analyses performed on commercial applications integrate several sources of uncertainty, such as the uncertainty introduced from the instrumentation of the experimental measurements, the statistical uncertainty introduced from the regression model employed for the determination of the thermal boundary condition at the heated bottom (basement) wall of the AM cooling channel and the numerical discretisation error inherited in CFD simulations.

The second primitive variable investigated for the numerical characterisation of the cryogenic coolant flow in the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator is the coolant pressure. In Fig. 8, the average coolant pressure value of

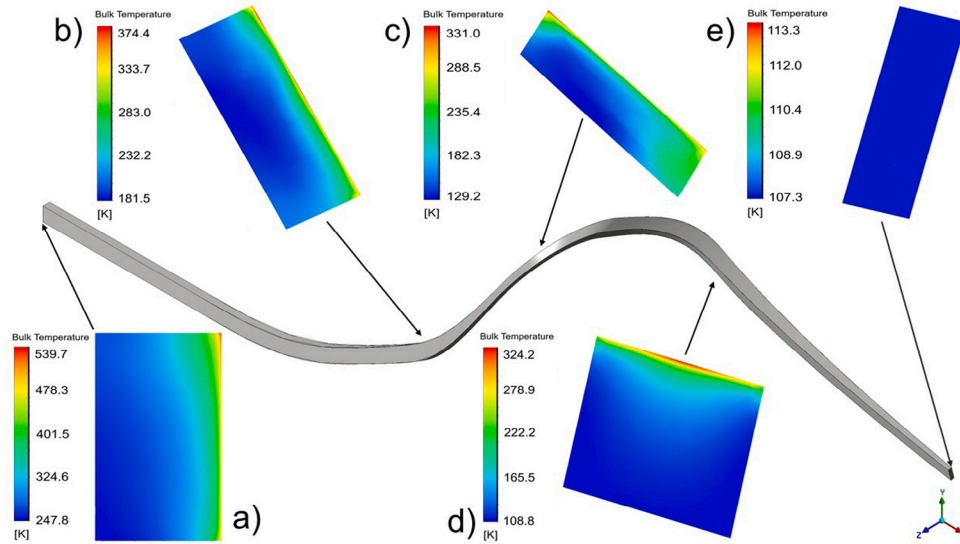


Fig. 9. Bulk temperature variation across longitudinal coordinate of cryogenic coolant side at (a) Outlet ($z = 0$ [m]), (b) Throat exit ($z = 0.12$ [m]), (c) Throat ($z = 0.14$ [m]), (d) Throat beginning ($z = 0.16$ [m]) and (e) Inlet ($z = 0.22$ [m]) sections.

the cryogenic liquid oxygen in the different cross-sections uniformly distributed across the longitudinal coordinate of the cryogenic coolant side is also exhibited. As seen, the cryogenic propellant enters the inlet section of the AM microfluidic cooling channel at a high coolant pressure of approximately 195 [bar]. A reduction of the average coolant pressure of the cryogenic coolant is observed across the range of the longitudinal coordinate of the cryogenic coolant side. Ultimately, at the outlet section of the microfluidic cooling channel of the liquid rocket engine, the value of the average coolant pressure appears to converge to the fixed value of $P = P_{out} = 57.1$ [bar], which as discussed in Section 2.3, has been imposed as a Dirichlet-type pressure outlet boundary condition at the commercial CFD package ANSYS Fluent. A comprehensive determination of the pressure-field development across the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator additionally requires the determination of the total pressure drop, furthermore to the quantification of the pressure drop at the corresponding distinct regions of the AM cooling channel. In this matter, as indicated in Fig. 8, it is significant to quantify the amount of pressure drop observed by the time the counterflowing cryogenic coolant exits the throat region of the AM cooling channel at the longitudinal coordinate $z = 0.12$ [m]. The total pressure drop of the cryogenic liquid oxygen from the inlet up to the outlet section of the AM cooling channel of the liquid rocket engine is estimated to be 136.79 [bar]. In this case, the amount of pressure drop computed up to the point that the counterflowing cryogenic coolant exits the throat region of the AM cooling channel is computed as 120.85 [bar], which is considerable, as it accounts for approximately 88% of the total pressure drop. As a result, the importance of the design guidelines that need to be satisfied in the additive manufacturing process of the microfluidic cooling channel of strong curvature at the throat region of the aerospike engine where high heat fluxes are applied, is highlighted [40].

The secondary primitive variables of the cryogenic coolant velocity and density in the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator investigated in the present study are exhibited in Fig. 10. Initially, the average coolant velocity of the cryogenic propellant in the uniformly distributed cross-sections across longitudinal coordinate of the AM cooling channel is shown in Fig. 10. A decisive parameter for the determination of the cryogenic coolant velocity at the inlet section of the AM cooling channel is the mass flow rate at the corresponding channel section. As discussed in Section 2.3, a Dirichlet-type mass flow rate boundary condition of fixed value equal to $\dot{m} = 0.08$ [kgs⁻¹] has been imposed at the inlet section

of the microfluidic cooling channel on the commercial CFD package. As the cryogenic coolant counterflows from the base to the injector head of the liquid rocket engine, non-uniform heat fluxes are applied from the heated bottom (basement) wall of the AM cooling channel, resulting in an overall velocity increment of the cryogenic propellant. More specifically, at the inlet section of the microfluidic cooling channel a relatively-low coolant velocity of approximately 36 [ms⁻¹] is recorded. However, as indicated in Fig. 10, an adverse acceleration of the cryogenic coolant is observed at the throat region of the AM cooling channel. This increment of the average cryogenic coolant velocity at the throat region of the cooling channel is a consequence of the design considerations for the reduction of the fluidic width available at the throat region exhibited in Fig. 3, for the satisfaction of the enhanced thermal demands at the corresponding channel region. Following the exit of the counterflowing cryogenic coolant from the throat region, an insignificant deceleration is observed, as the propellant recovers its momentum as it flows towards the outlet section of the AM cooling channel of the DemoP1 aerospike engine demonstrator. The coolant velocity magnitude variation across the variable, rectangular cross-sections of the AM cooling channel of the DemoP1 aerospike engine demonstrator is exhibited in Fig. 11. According to Fig. 11, the coolant velocity at the inlet section is fixed and estimated as approximately 36 [ms⁻¹]. A fully-developed cryogenic coolant flow is observed at the beginning of the throat ($z = 0.16$ [m]), whilst larger variations of the coolant velocity are observed at the throat region of the microfluidic cooling channel. As discussed, this is attributed to the strong curvature reported at the throat region of the cooling channel, the higher heat-flux applied from the hot-gas side to the coolant side and the reduction of the available fluidic width at the corresponding cooling channel region. Finally, note that in Fig. 11 a three-dimensional representation of the microfluidic cooling channel is demonstrated. For clarity purposes however, the investigated cross-sections across the longitudinal coordinate of the microfluidic cooling channel are exhibited in an XY coordinate plane.

The average coolant density of the cryogenic liquid oxygen at the different cross-sections of the Additively Manufactured (AM) microfluidic cooling channel of the DemoP1 aerospike engine demonstrator is now presented. The computed values of the average coolant density at the different cross-sections across the AM cooling channel are reported in Fig. 10. The cryogenic coolant enters the AM cooling channel characterised by a relatively high density of approximately 700 [kgm⁻³]. As the cryogenic propellant counterflows from the rocket engine base

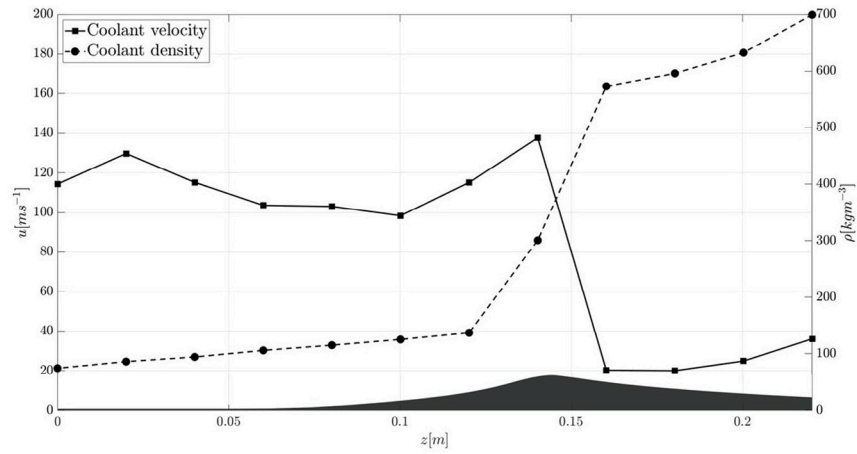


Fig. 10. Average coolant velocity and coolant density at different cross-sections across longitudinal coordinate of cryogenic coolant side.

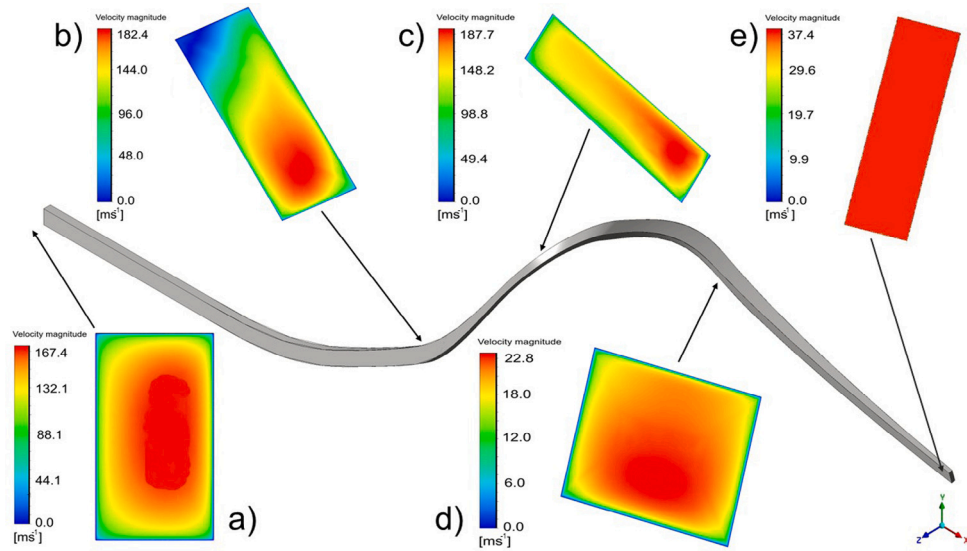


Fig. 11. Coolant velocity magnitude variation across longitudinal coordinate of cryogenic coolant side at (a) Outlet ($z = 0$ [m]), (b) Throat exit ($z = 0.12$ [m]), (c) Throat ($z = 0.14$ [m]), (d) Throat beginning ($z = 0.16$ [m]) and (e) Inlet ($z = 0.22$ [m]) sections.

to the throat region of the AM cooling channel, minor coolant density variations are reported. At the throat region, however, where the three-dimensional geometric configuration is characterised by a very-strong curvature, an adverse average coolant density reduction is observed. More specifically, at the throat region ranging from a longitudinal coordinate of $z = 0.12$ [m] to $z = 0.16$ [m], the average cryogenic coolant density reduction is estimated as 435.88 [kgm^{-3}]. Note that by the time the cryogenic liquid oxygen exits the throat region of the AM cooling channel, approximately 90% of the total coolant density reduction has already been observed. At the outlet section of the microfluidic cooling channel, the average coolant density of the cryogenic propellant counterflowing across the AM cooling channel is computed as roughly 75 [kgm^{-3}].

In the last part of this section, the thermophysical properties of dynamic viscosity, specific heat capacity at constant pressure and thermal conductivity of the cryogenic liquid oxygen at the different cross-sections uniformly distributed at the different cross-sections of the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator are reported. As shown in Figs. 12 and 13, the thermophysical properties of the cryogenic coolant exhibit a similar trend to the average bulk temperature at the different cross-sections

across the longitudinal coordinate of the coolant side demonstrated in Fig. 8. In addition to the average temperature gain identified, the thermophysical properties of dynamic viscosity, specific heat capacity at constant pressure and thermal conductivity of the cryogenic propellant also appear to increase, as the cryogenic coolant counterflowing in the AM cooling channel receives the non-uniform heat load from the hot-gas of the liquid rocket engine demonstrator on the bottom (basement) wall boundary of the cooling channel. More specifically, as exhibited in Fig. 12, the cryogenic coolant enters the microfluidic cooling channel at a dynamic viscosity equal to $8.65 \cdot 10^{-6}$ [Pa s] and exits the AM cooling channel at a dynamic viscosity value computed as $2.25 \cdot 10^{-5}$ [Pa s]. In the case of the thermophysical property for the specific heat capacity at constant pressure in Fig. 13, the cryogenic coolant at the inlet section of the AM cooling channel is characterised by a specific heat capacity value of roughly 913 [$\text{Jkg}^{-1}\text{K}^{-1}$] and a value of approximately 919 [$\text{Jkg}^{-1}\text{K}^{-1}$] at the outlet section of the microfluidic channel of the liquid rocket engine demonstrator. Finally, with respect to the thermophysical property for the thermal conductivity of the cryogenic liquid oxygen exhibited in Fig. 13, the thermal conductivity of the propellant is computed as roughly 0.01 [$\text{Wm}^{-1}\text{K}^{-1}$] and 0.03 [$\text{Wm}^{-1}\text{K}^{-1}$] at the inlet and outlet sections of the AM cooling channel,

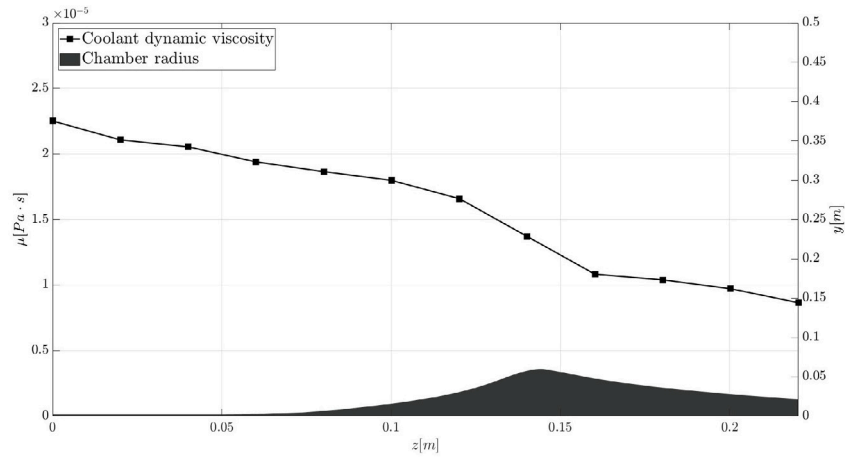


Fig. 12. Average coolant dynamic viscosity of cryogenic liquid oxygen at different cross-sections across longitudinal coordinate of cryogenic coolant side.

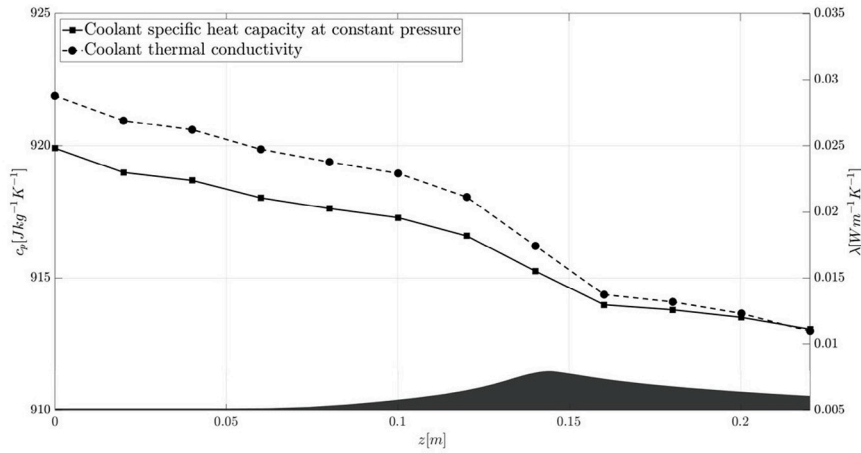


Fig. 13. Average coolant specific heat capacity at constant pressure of cryogenic liquid oxygen at different cross-sections across longitudinal coordinate of cryogenic coolant side.

respectively. Note that, similar to the development of the average bulk temperature-field of the cryogenic coolant, an adverse gradient is observed at the throat region in comparison with the remaining regions of the AM cooling channel, for each thermophysical property investigated in the present study.

The first step for the implementation of a numerical analysis to characterise the cryogenic liquid oxygen flow in the Additively Manufactured (AM) microfluidic cooling channel of the DemoP1 aerospike engine demonstrator is based on the determination of the four primitive variables, in addition to the thermophysical properties of the investigated fluid, presented in this section. For the assessment of the performed simulation on the commercial CFD package, the numerical solution for the average cryogenic coolant temperature at the outlet section of the microfluidic cooling channel is compared against the corresponding experimentally measured value obtained from the hot-fire testing campaign of the DemoP1 aerospike engine demonstrator. The results indicate very good agreement of the numerical solution with the experimental data on the average bulk temperature of the cryogenic propellant at the outlet section of the AM cooling channel; more specifically, a percentage deviation of 0.73% is observed between the two values, which is within an acceptable range for high-heat flux aerospace applications. In the subsequent section, a numerical procedure for the characterisation of the thermal behaviour of the

cryogenic liquid oxygen flow in the AM cooling channel of the DemoP1 aerospike engine demonstrator in terms of Nusselt number is presented.

3.3. Nusselt number correlation deduction

The determination of the thermal characteristics of the cryogenic liquid oxygen flow in the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator in terms of Nusselt number, requires the collection of numerical measurements from the different cross-sections across the longitudinal coordinate of the microfluidic cooling channel. Prior to the deduction of a Nusselt number correlation for the characterisation of the thermal behaviour of the cryogenic propellant in the AM cooling channel, a numerical analysis with respect to the average values of the dimensionless numbers in the different cross-sections uniformly distributed across the microfluidic cooling channel is performed. Note that the deduction of a Nusselt number correlation requires the estimation of the Reynolds and Prandtl numbers, defined as follows

$$Re = \frac{\rho u D_h}{\mu} \text{ and } Pr = \frac{\mu c_p}{\lambda}, \quad (7)$$

where the parameters in Eq. (7) denote average quantity values at the corresponding cross-section across the longitudinal coordinate of

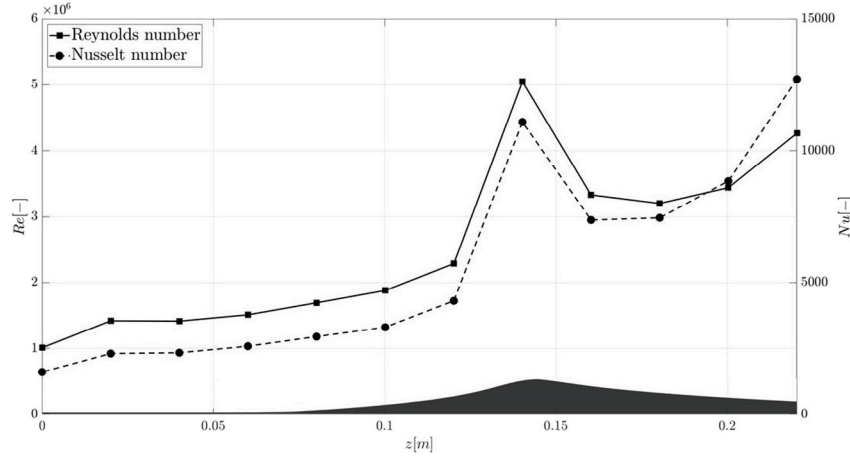


Fig. 14. Average Reynolds and Nusselt numbers characterising cryogenic liquid oxygen flow at different cross-sections across longitudinal coordinate of cryogenic coolant side.

the Additively Manufactured (AM) cooling channel; ρ indicates the density of the cryogenic coolant, u the coolant velocity, D_h the hydraulic diameter, μ the fluid dynamic viscosity, c_p the fluid specific heat capacity at constant pressure and λ the thermal conductivity of the cryogenic coolant at the corresponding cross-section. Furthermore, assuming a bulk temperature T_b identical to the imposed thermal boundary condition on the commercial CFD package and equal to $T_{in} = 107.4$ [K], the average fluid-to-bulk temperature ratio at the different cross-sections across the AM cooling channel is defined as T/T_b . Contrary to the computational example of a uniformly heated circular tube, the determination of the Nusselt number in the case of a three-dimensional, rough, microfluidic channel of variable, rectangular cross-section characterised by a strong curvature and that is heated in a non-uniform manner, is not straightforward. For the determination of the Nusselt number in the AM cooling channel of the DemoP1 aerospike engine demonstrator, typical correlations introduced in the literature for smooth and rough wall bounded flows are employed. Initially, the Gnielinski correlation for the estimation of the dimensionless Nusselt number in smooth tubes, in addition to its correction formulation introduced by Norris to account for rough surfaces of the investigated flow [50], provide an indicator for the characterisation of the thermal behaviour of the cryogenic coolant flow in the AM cooling channel. The Nusselt number correlations for the determination of the thermal characteristics are reported in the literature as follows

$$\text{Gnielinski correlation: } Nu_s = \frac{(f_s/8)(Re - 1000)Pr}{1 + 12.7(f_s/8)^{1/2}(Pr^{2/3} - 1)}, \quad (8)$$

$$\text{Norris correction: } Nu_r = Nu_s \left(\frac{f_r}{f_s} \right)^{0.68(Pr^{0.215})}, \quad (9)$$

where the s and r subscripts indicate the corresponding average variable values at the different cross-sections across the longitudinal coordinate of the Additively Manufactured (AM) cooling channel for smooth and rough surfaces. The average value of the friction factor for smooth, f_s , and rough, f_r , surfaces is determined based on the Colebrook equation [51] written as

$$\frac{1}{\sqrt{f}} = -2 \log_{10} \left(0.27 \frac{k_s}{D_h} + \frac{2.51}{Re \sqrt{f}} \right), \quad (10)$$

where as discussed in Appendix, the equivalent sand-grain roughness height at the wall boundaries of the Additively Manufactured (AM) microfluidic cooling channel of the DemoP1 aerospike engine demonstrator is determined as $k_s = 49.17$ [μm]. In the case of the smooth wall boundaries, the friction factor, f_s is estimated by imposing a roughness height value equal to zero, $k_s = 0$ [μm]. As shown, the numerical solution of Eq. (10) for the determination of the friction factor requires

an iterative process. Note that in both cases for smooth and rough surfaces, the iterative process for the solution of the Colebrook equation required a maximum of 9 iterations to reach the threshold tolerance of 10^{-9} , for the deviation between two consecutive estimations of the friction factor variable. Furthermore to the determination of the friction factor for the cryogenic propellant flow in the AM cooling channel of the liquid rocket engine demonstrator based on the Colebrook equation reported in Eq. (10), Haaland's equation is also investigated [52]. The explicit universal formula for the friction factor in turbulent flows introduced by Haaland reads

$$\frac{1}{\sqrt{f}} = -1.8 \log_{10} \left[\frac{6.9}{Re} + \left(\frac{k_s}{3.7 D_h} \right)^{1.11} \right]. \quad (11)$$

In the present numerical investigation, the friction factor of the cryogenic liquid oxygen in the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator is determined as the maximum value between the solution obtained from the Colebrook equation in Eq. (10) and the Haaland equation in Eq. (11). The aforementioned correlations correspond to the definition of the constant property flow friction factor based on the Reynolds number of the flow, in addition to the hydraulic diameter and the roughness height of the wall boundaries in the investigated microfluidic flow. To account for the effects of the non-adiabatic case, Petukhov [53] introduced a correction factor based on the fluid-to-bulk temperature ratio defined as $c_f = (T/T_b)^{-0.52}$. Ultimately, the estimated friction factor for the smooth and rough surface is introduced in the Gnielinski correlation in Eq. (8) and the Norris correction in Eq. (9), allowing for the estimation of the dimensionless Nusselt number of the cryogenic coolant. The dimensionless numbers characterising the cryogenic liquid oxygen flow at the different cross-sections across the longitudinal coordinate of the AM cooling channel of the liquid rocket engine demonstrator are exhibited in Figs. 14 and 15.

As shown, the dimensionless average Reynolds and Nusselt numbers characterising the cryogenic liquid oxygen flow at the different cross-sections of the Additively Manufactured (AM) cooling channel in Fig. 14, exhibit similar trends. This similarity can be attributed to the fact that according to the Gnielinski correlation reported in Eq. (8), the dimensionless Nusselt number is proportional to the Reynolds number of the investigated flow. The cryogenic coolant enters the AM cooling channel of the DemoP1 aerospike engine demonstrator characterised by the dimensionless numbers of $Re = 4.26 \cdot 10^6$, $Nu = 12,713$ and $Pr = 0.720$. At the throat region of the AM cooling channel at the longitudinal coordinate $z = 0.14$ [m], an adverse increment of the dimensionless average Reynolds and Nusselt numbers is observed. More specifically, the average Reynolds and Nusselt numbers at the throat region of the microfluidic cooling channel are equal to approximately

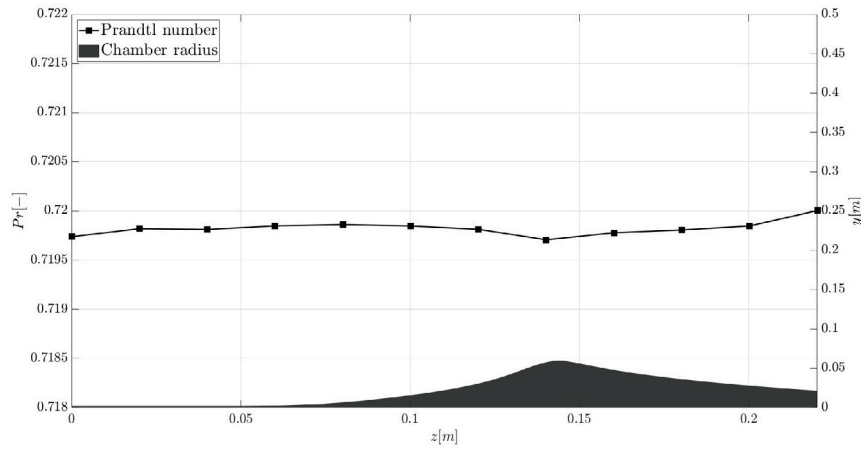


Fig. 15. Average Prandtl number characterising cryogenic liquid oxygen flow at different cross-sections across longitudinal coordinate of cryogenic coolant side.

$Re = 5.05 \cdot 10^6$ and $Nu = 11,086$, respectively. As discussed in Section 2.2, the reduction of the fluidic width available at the throat region to enhance the cooling capabilities of the AM microfluidic channel, results in a significant increment of the cryogenic coolant velocity at the corresponding cooling channel region and therefore, an overall increment of the average Reynolds number. As the cryogenic propellant exits the throat region and counterflows towards the outlet section of the microfluidic cooling channel, a reduction of the dimensionless average Reynolds and Nusselt numbers is observed, i.e., the cryogenic coolant exits the AM cooling channel at a Reynolds number equal to $1.01 \cdot 10^6$ and a Nusselt number computed as roughly 1607. With respect to the average Prandtl number at the different cross-sections across the AM cooling channel, the deviations in the evaluation of the dimensionless number are trivial. In particular, as exhibited in Fig. 15, the average Prandtl number values across the longitudinal coordinate of the AM cooling channel balance around the value of 0.72. Considering the increment of the thermophysical properties of the cryogenic liquid oxygen at the throat region of the AM cooling channel exhibited in Figs. 12 and 13 and the definition of the dimensionless Prandtl number reported in Eq. (7), the minor reduction of the average Prandtl number at the throat region of the microfluidic cooling channel reveals the predominance of the fluid thermal conductivity in the determination of the dimensionless Prandtl number.

Subsequent to the determination of the dimensionless average Nusselt number at the different cross-sections across the longitudinal coordinate of the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator, a comparison between the computed values of the friction factor and the corresponding dimensionless number for smooth and rough surface flows is demonstrated in Figs. 16 and 17. The determination of the average friction factor at the different cross-sections across the microfluidic cooling channel originates in the solution of the Colebrook and the Haaland equations reported in Eqs. (10) and (11), respectively, and is obtained as the maximum value amongst the two solutions. In Fig. 16, a comparison between the computed average values of the friction factor across the AM cooling channel is performed in the case of smooth, $k_s = 0$ [μm], and rough, $k_s = 49.17$ [μm], surfaces. As expected, the average friction factor value in the case of the rough surface flow estimated at each cross-section of the microfluidic cooling channel is significantly larger than the corresponding value in the case of a smooth surface flow. More specifically, the estimated friction factor in the case of a smooth surface flow is on average roughly 20% the magnitude of the friction factor computed for rough surfaces in the AM cooling channel. At the inlet and throat region of the AM cooling channel located at the longitudinal coordinate of $z = 0.22$ [m] and $z = 0.14$ [m], respectively, the deviation

between the estimated friction factor for smooth and rough surfaces is magnified. At the inlet section, the friction factor estimated in the case of a smooth surface is 15.31% of the corresponding value computed for rough surfaces, whilst at the throat region of the AM cooling channel the corresponding percentage is determined as 15.79%. The average dimensionless Nusselt number estimated according to the Gnielinski correlation reported in Eq. (8) and the Norris correlation in Eq. (9), is exhibited in Fig. 17. Inevitably, the Norris correction on the Gnielinski correlation to account for rough surfaces in the walls of the investigated bounded flow predicts larger values in comparison with the average Nusselt number estimation computed for smooth surfaces. The mean deviation between the average Nusselt number estimated using the Gnielinski correlation and the Norris correction across the AM cooling channel of the DemoP1 aerospike engine demonstrator is computed as 65%. In summary, the friction factor and the dimensionless Nusselt number estimated in the case of rough wall boundaries for the investigated bounded flows are notably larger in comparison with the corresponding values computed for smooth wall boundaries.

Furthermore, the average heat transfer coefficient at the different cross-sections across the longitudinal coordinate of the Additively Manufactured (AM) cooling channel of the liquid rocket engine can be estimated as $h_c = (Nu \cdot k)/D_h$. In Fig. 18, it is shown that the computed average heat transfer coefficient exhibits similar trends with the determined dimensionless average Nusselt number at the different cross-sections of the AM cooling channel demonstrated in Fig. 14. More specifically, the global maximum value of the average heat transfer coefficient is observed at longitudinal coordinate of $z = 0.14$ [m] at the throat region of the AM cooling channel and is computed as $115,595$ [$\text{Wm}^{-2}\text{K}^{-1}$]. At the inlet section, the average heat transfer coefficient is comparable to the magnitude of the coefficient at the throat region and evidently larger than the remaining sections of the microfluidic cooling channel and is computed as roughly $95,400$ [$\text{Wm}^{-2}\text{K}^{-1}$]. After the inlet section, the average heat transfer coefficient tends to decrease, whilst the parameter gradient changes as the cryogenic coolant enters the throat region. As the cryogenic propellant counterflows towards the outlet section of the AM cooling channel, the average heat transfer coefficient appears to monotonically decrease as it reaches the outlet section of the cooling channel, where it is characterised by an average heat transfer coefficient equal to approximately $17,300$ [$\text{Wm}^{-2}\text{K}^{-1}$].

For the determination of the heat transfer characteristics for the cryogenic liquid oxygen flow in the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator, measurements of fluid flow variables at different locations in the uniformly distributed cross-sections across the longitudinal coordinate of the cooling channel are obtained. These measurements for the dimensionless

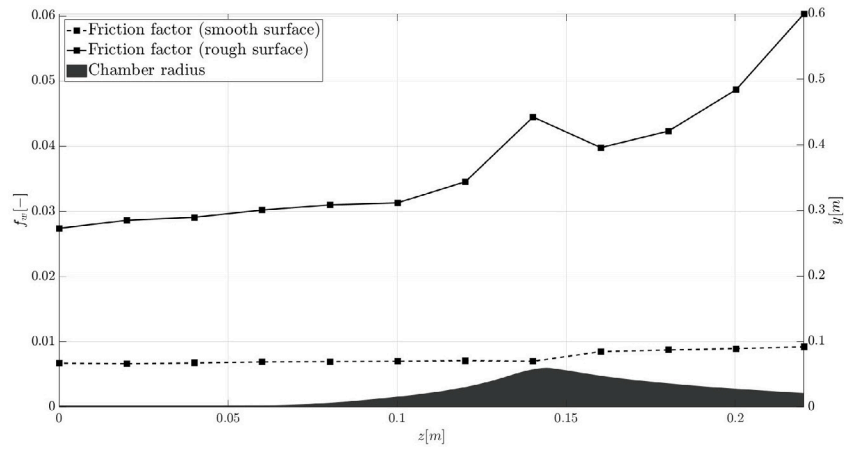


Fig. 16. Differentiation between average friction factor estimation for smooth and rough surface flow at different cross-sections across longitudinal coordinate of cryogenic coolant side.

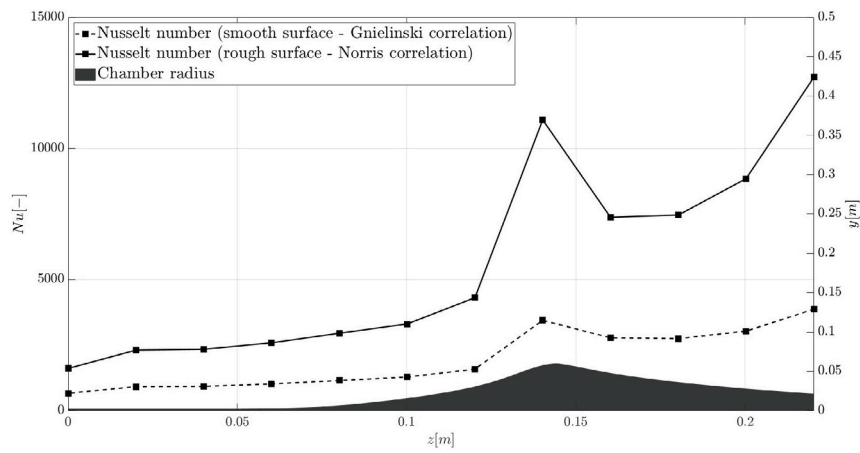


Fig. 17. Differentiation between average Nusselt number estimation for smooth and rough surface flow at different cross-sections across longitudinal coordinate of cryogenic coolant side.

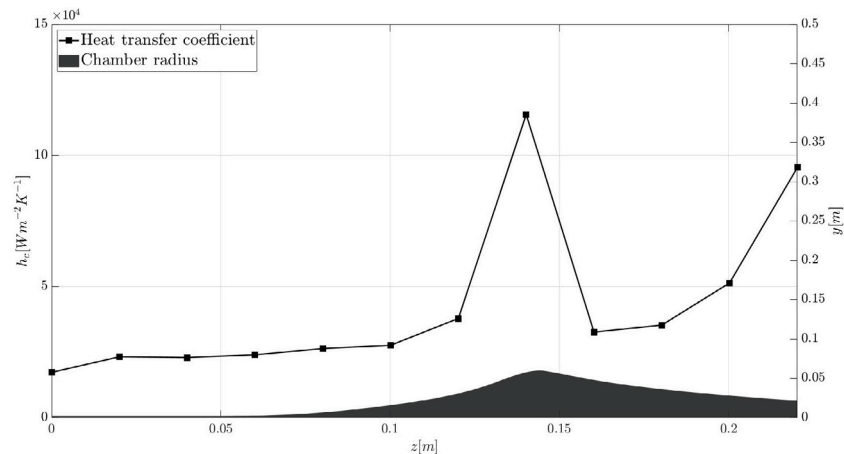


Fig. 18. Average heat transfer coefficient at different cross-sections across longitudinal coordinate of cryogenic coolant side.

numbers at different locations across the microfluidic cooling channel provide the required input data for the deduction of a peculiar Nusselt number correlation, describing the thermal behaviour of the cryogenic coolant in the AM cooling channel of the liquid rocket engine demonstrator. The numerical setup includes the measurement of the primitive variables of temperature, density and velocity for the

cryogenic coolant, in addition to measurements for the thermophysical properties of the fluid dynamic viscosity, specific heat capacity at constant pressure and thermal conductivity. The obtained measurements are then employed for the determination of the dimensionless Reynolds, Prandtl and Nusselt number, furthermore to the estimation of the fluid-to-bulk temperature ratio T/T_b at each location investigated

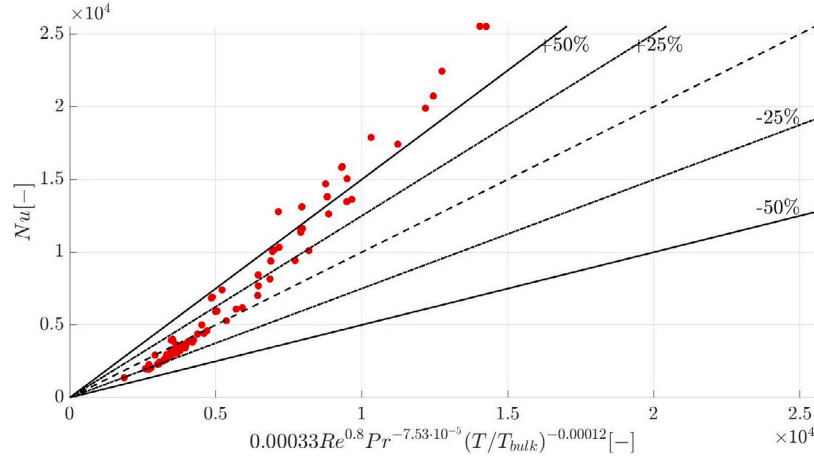


Fig. 19. Numerical measurements at different locations across cryogenic coolant side on Nu_{corr} - Nu diagram based on Eq. (14).

across the AM cooling channel. In the 12 different rectangular cross-sections, 9 locations are selected including the centroid and diagonals of each cross-section, resulting in a total of 108 measurements across the microfluidic cooling channel.

As discussed, the measurements collected from the different locations of the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator are utilised for the characterisation of the thermal behaviour of the cryogenic coolant flow in terms of Nusselt number. Initially, considering the whole set of numerical measurements at the different locations in the cross-sections uniformly distributed across the longitudinal coordinate of the microfluidic cooling channel, the computed Reynolds number ranges from $8.01 \cdot 10^5$ to $1.02 \cdot 10^7$, the Nusselt number from 1368.41 to 25,535.19, the Prandtl number balances around the value of 0.72 and the fluid-to-bulk temperature ratio from 0.99 to 2.99. In the case of high-heat fluxes applied at the wall boundaries of the cryogenic coolant flow, the employment of the conventional Dittus–Boelter correlation [54] for the characterisation of the fluid flow thermal behaviour becomes ambiguous. Hence, the introduction of a modified Dittus–Boelter correlation for the determination of the heat transfer characteristics of the cryogenic liquid oxygen flow in the AM cooling channel of the aerospike engine demonstrator is required. To account for the variation of the cryogenic fluid thermophysical properties, a correction factor is included based on the fluid-to-bulk temperature ratio, resulting in the modified Dittus–Boelter correlation of the form

$$Nu_{corr} = \alpha Re^{0.8} Pr^{\beta} \left(\frac{T}{T_b} \right)^{\gamma}, \quad (12)$$

where α , β and γ are the correlation coefficients to be estimated for the determination of the peculiar modified Dittus–Boelter correlation and Nu_{corr} is the Nusselt number correlated with the obtained numerical measurements in the different locations across the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator. Similar to an experimental investigation of transcritical methane flow in a rocket engine cooling channel performed by Votta et al. [24], an exponent equal to 0.8 is imposed on the Reynolds number according to the Reynolds analogy in the case of turbulent flows. For the determination of the correlation coefficients α , β and γ , the minimisation of the root-mean-square (RMS) error RMS_e is required. The evaluation of the RMS_e parameter is based on the dimensionless Nusselt number obtained from the Norris correction reported in Eq. (9) and the correlated Nusselt number in Eq. (12) as

$$RMS_e = \sqrt{\sum_{i=1}^N \left(\frac{Nu_{corr,i} - Nu_i}{Nu_i} \right)^2} / N \quad (13)$$

where $N = 108$ is the total number of numerical measurements obtained at the different locations in the rectangular cross-sections across the longitudinal coordinate of the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator. The minimisation of the root-mean-square (RMS) error through the solution of the unconstrained multivariable function results in the determination of the correlation coefficients as $\alpha = 0.00033$, $\beta = -7.53 \cdot 10^{-5}$ and $\gamma = -0.00012$. Thus, the peculiar modified Dittus–Boelter correlation for the characterisation of the cryogenic coolant in the AM cooling channel reads

$$Nu_{corr} = 0.00033 \cdot Re^{0.8} Pr^{-7.53 \cdot 10^{-5}} \left(\frac{T}{T_b} \right)^{-0.00012}. \quad (14)$$

The minimum generic i th error between the Nusselt number correlated with the numerical measurements obtained from the different locations across the longitudinal coordinate of the microfluidic cooling channel and the Nusselt number determined according to the Norris correction reported in Eq. (9) is 0.002%, whilst the maximum error is computed as approximately 45%. A qualitative representation of the accuracy characterising the proposed modified Dittus–Boelter correlation in Eq. (14) for the description of the heat transfer characteristics of the cryogenic coolant flow in the Additively Manufactured (AM) cooling channel of the liquid rocket engine is demonstrated in Fig. 19.

As seen in Fig. 19, the majority of the numerical measurements obtained from the different locations across the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator are scattered around the bisector of the plot and exhibit an uncertainty in the range of $\pm 25\%$. More specifically, approximately 74% of the numerical measurements lie within the $\pm 25\%$ uncertainty range. In the case of low Nusselt number estimations up to 5000 based on the proposed modified Dittus–Boelter correlation reported in Eq. (14) and the Norris correction in Eq. (9), the numerical data are predominantly characterised by an uncertainty of -25% . Note that in dimensionless Nusselt number values larger than 10,000, the uncertainty of the whole set of numerical measurements appears to exceed $+50\%$. More specifically, merely 13% of the numerical measurements obtained across the microfluidic cooling channel are scattered outside the uncertainty range of $\pm 50\%$. Overall, Fig. 19 suggests that the Dittus–Boelter correlation introduced in Eq. (14) underpredicts the dimensionless Nusselt number at the corresponding locations across the AM cooling channel comparing to the predictions of the Norris correction exhibited in Eq. (9). The modified Dittus–Boelter correlation reported in Eq. (14) is therefore suggested for the characterisation of the thermal behaviour of relatively-low Nusselt number cryogenic coolant flows in asymmetrically heated microfluidic cooling channels of variable, rectangular cross-section exhibiting a strong curvature.

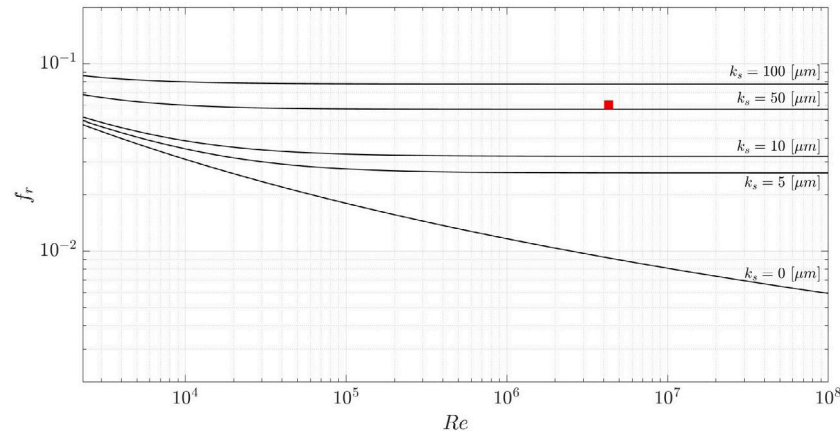


Fig. 20. Moody-like diagram of the numerical measurements at different locations across cryogenic coolant side.

In the last part of this section, the roughness height of the wall boundaries of the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator is estimated based on an extracted Moody-like diagram and compared against the equivalent sand-grain roughness height obtained according to the analysis presented by Brackbill and Kandlikar [55]. As discussed in Appendix, the equivalent sand-grain roughness height estimated by means of optical profilometry in an AM metallic sample of the DemoP1 aerospike engine demonstrator is equal to $k_s = 49.17 \text{ } [\mu\text{m}]$. In Fig. 20, five friction factor lines characterised by a roughness height ranging from 0 to 100 $[\mu\text{m}]$ are depicted. The dimensionless Reynolds number in the Moody-like diagram ranges from 2300 to 10^8 . In the present numerical analysis, the selection of the cross-section across the microfluidic cooling channel does not significantly affect the obtained results. Therefore, the investigated rectangular cross-section of the microfluidic cooling channel is selected at the interim of the throat region at the longitudinal coordinate, $z = 0.14 \text{ } [\text{m}]$, which as discussed in Section 2.2, is considered the most computationally challenging due to the increased heat loads applied. For the implicit solution of the Colebrook equation reported in Eq. (10) for the determination of the friction factor in the case of constant properties flow in tubes of high roughness, the average friction factor and the dimensionless Reynolds number variables at the corresponding cross-section of the AM cooling channel are assigned to symbolic variables. As shown in Fig. 20, the data for the estimated roughness height of the AM wall boundaries is located slightly above the friction factor line of $k_s = 50 \text{ } [\mu\text{m}]$. As a result, the percentage deviation between the estimation for the equivalent sand grain roughness height estimated by means of optical profilometry measurements on the AM sample of the liquid rocket engine demonstrator in conjunction with the roughness approach proposed by Brackbill and Kandlikar [55] and the roughness height obtained by means of the Moody-like diagram exhibited in Fig. 20, are trivial. This justifies the accurate and physically correct prediction of the velocity and temperature fields obtained from the numerical simulations performed in the current investigation. As discussed, the deviation of the numerically predicted average bulk temperature of the coolant at the outlet section of the AM channel and the experimental data was quantified as 0.73%. As a result, the comparison between the different estimations of the roughness height together with the validation of the numerical model against the experimental data of the outlet coolant average bulk temperature provide a further justification of the accurate and physically correct prediction of the velocity and temperature fields obtained from the numerical simulations.

4. Conclusions

In the current work, a numerical characterisation of the cryogenic liquid oxygen flow in the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator is presented. The geometric configuration of interest regards a three-dimensional, microfluidic cooling channel of variable, rectangular cross-section and strong curvature at the throat region of the aerospike engine demonstrator. For the characterisation of the cryogenic fluid flow in the AM cooling channel of the liquid rocket engine, the development of the primitive variables in addition to the thermophysical properties and the dimensionless numbers of the cryogenic fluid across the microfluidic cooling channel are investigated. The assessment of the numerical solution from the CFD simulation is performed through a comparison against experimental measurements obtained from the full-scale, single-injector element hot-fire testing campaign of the DemoP1 aerospike engine demonstrator. In this context, the percentage deviation between the numerical and the experimentally measured value of the cryogenic coolant temperature at the outlet section of the AM cooling channel is estimated. Additionally, the present study focuses on the derivation of a peculiar Nusselt number correlation for the characterisation of the heat transfer behaviour of the cryogenic fluid in the variable, rectangular cross-section cooling channel of the liquid rocket engine demonstrator.

The key findings of the current work are summarised as follows. Initially, the numerical solution obtained exhibits a very good agreement with the experimental data available from the hot-fire testing campaign of the DemoP1 aerospike engine demonstrator. More specifically, the percentage deviation of the numerical solution obtained for the cryogenic fluid temperature at the outlet section of the microfluidic cooling channel against the corresponding value obtained from experimental measurements is 0.73%. With respect to the dimensionless numbers characterising the flow-field and heat transfer development across the Additively Manufactured (AM) cooling channel, the experienced Reynolds number ranges from $8.01 \cdot 10^5$ to $1.02 \cdot 10^7$, the Nusselt number from 1368.41 to 25,535.19, the Prandtl number balances around the value of 0.72 and the fluid-to-bulk temperature ratio is in the range from 0.99 to 2.99. The enhanced heat transfer capabilities of the cooling channel with high roughness inherited by the additive manufacturing process in comparison with a channel with smooth surfaces are also exhibited. In particular, the friction factor and dimensionless Nusselt number estimations for a channel with smooth surfaces are estimated as approximately 20% and 65%, respectively, of the corresponding magnitude values of the high roughness cooling channel of the DemoP1 aerospike engine demonstrator. Finally,

a peculiar Nusselt number correlation in accordance with a modified Dittus–Boelter correlation for asymmetrically heated microfluidic cooling channels of variable, rectangular cross-sections with a strong curvature is introduced. It is shown that the majority of the numerical measurements lie within the $\pm 25\%$ uncertainty range, particularly in the case of Nusselt number values below 10,000. In summary, the present numerical investigation for the numerical characterisation of the cryogenic liquid oxygen flow in the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator constitutes one of the first attempts to comprehend the thermal behaviour of the cryogenic propellant in the dual regenerative cooling system of a high-heat flux aerospace application.

Following the further development of the investigated DemoP1 aerospike engine demonstrator, future work shall also include further experimental validation of the numerical model proposed in the current investigation. More specifically, a potential increment in the available instrumentation shall allow for more available experimental measurements regarding the primitive variables characterising the cryogenic coolant flow in the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator. This will not only allow for an extensive experimental validation of the implemented numerical model presented in the current work, but shall additionally allow to further comprehend the high roughness, turbulent fluid flow mechanisms inside the asymmetrically heated, cooling channel of the aerospike engine demonstrator. Subsequently, this will also allow for the employment of the real-gas law for the characterisation of the cryogenic coolant flow in the AM cooling channel. Following the preliminary thermal analysis presented in the current work, heavier experimental instrumentation inside the cooling channel shall permit for the identification of the coolant phase variation across the coolant side. Due to the setup of the experimental activity and the enhanced heat loads applied from the hot-gas side of the aerospike engine to the cooling channel, liquid oxygen is expected to transition from the liquid to the transcritical phase at the throat region, reaching the outlet section of the cooling channel in supercritical (gaseous) conditions. Further experimental validation of the numerical model proposed in the current investigation shall allow for further comprehending the thermophysical properties of the oxygen working fluid in high-heat flux aerospace applications. Lastly, note that the Nusselt number correlation proposed in the present numerical investigation provides a relationship for the preliminary thermal characterisation of asymmetrically heated microfluidic cooling channels with variable rectangular cross-sections, exhibiting a strong curvature at the throat region. The proposed modified Dittus–Boelter correlation and the boundary condition specifications can be adapted and employed for cooling channels surrounding conventional and aerospike rocket engine nozzles, as it considers the enhanced thermal load demands encountered at the throat region of the nozzles. Knowing the velocity and temperature fields based on experimental data or numerical simulations, the dimensionless Reynolds and Prandtl numbers can be computed leading to the adaptability of the proposed Nusselt number correlation along with the specification of the boundary conditions for the thermal characterisation of nozzles in high-heat flux aerospace applications.

CRediT authorship contribution statement

Nikos Monokrousos: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **László Könözy:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Vassilios Pachidis:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Ernesto Sozio:**

Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Federico Rossi:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Estimation of cooling channel roughness height

The characterisation of the rough surfaces and the estimation of the roughness height of the wall boundaries of the three-dimensional, microfluidic curved channel of variable, rectangular cross-section is a necessary process for the numerical solution of cryogenic propellant flow in the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator. The numerical assessment of an irregular rough surface can be performed through the utilisation of statistical surface roughness parameters on the surface profile of the investigated sample. A synopsis on the definitions of several statistical surface roughness parameters is presented in [56]. The employment of statistical surface roughness parameters for the characterisation of rough surfaces relies on the compatibility of the investigated roughness parameters with the stochastic characteristics of the irregular distribution of the rough elements across the surface [57]. The deviation of the rough elements from the mean line is described either through vertical or horizontal indicators, with emphasis however placed on the former. A different classification of the statistical surface roughness parameters is based on whether the properties are obtained for a roughness profile (parameters denoted with R) or a rough surface area (parameters denoted with S). Details on the international standardisation of numerous statistical surface roughness parameters is available in the literature [58,59]. A summary of the statistical parameters, in addition to the discrete formulation for their estimation is reported in Table A.3.

For the estimation of the roughness height of the Additively Manufactured (AM) cooling channel wall boundaries, the equivalent sand-grain roughness height needs to be determined through measurements

Table A.3
Definition of statistical surface roughness parameters [57].

Parameter	Definition	Discrete formulation
EP_i	Evaluation profile	–
m	Mean line	$\frac{1}{n} \sum_{i=1}^n EP_i$
y_i	Roughness amplitude	$EP_i - m$
R_a	Arithmetic mean deviation	$\frac{1}{n} \sum_{i=1}^n y_i $
R_q	Root-Mean-Square roughness	$\sqrt{\frac{1}{n} \sum_{i=1}^n y_i^2}$
R_v	Maximum valley depth below mean line	$ \min y_i $
R_p	Maximum peak height above mean line	$\max y_i$
R_z	Maximum peak to valley height	$R_p + R_v$
s_k	Skewness	$\frac{1}{n(R_p)^3} \sum_{i=1}^n y_i^3$
k_u	Kurtosis	$\frac{1}{n(R_p)^4} \sum_{i=1}^n y_i^4$

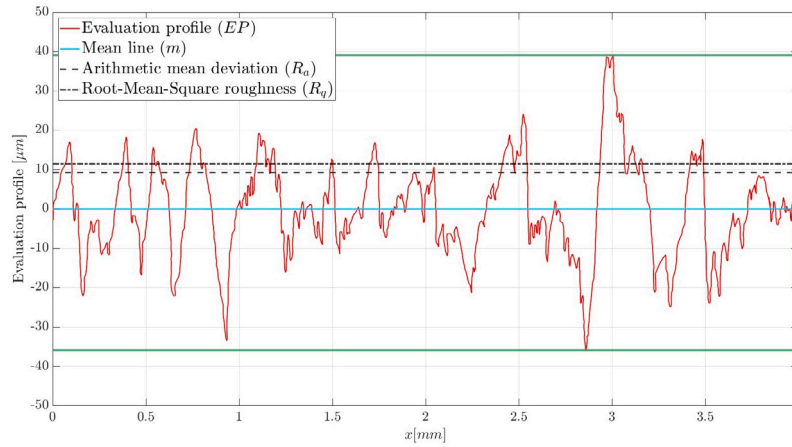


Fig. 21. Evaluation profile and statistical surface roughness parameters of the DemoP1 aerospike engine demonstrator sample.

obtained from an optical profilometry process on a metallic sample of the DemoP1 aerospike engine demonstrator. A comprehensive review on optical techniques for the measurement and characterisation of rough surfaces is presented in [59]. An important characteristic resulting from the employment of an additive manufacturing technique for the fabrication of a cooling channel for the dual regenerative cooling system of a liquid rocket engine, is the high and non-uniform, process-inherited surface roughness on the wall boundaries of the cooling channel. This effect constitutes a great challenge for the overall characterisation of the heat transfer and pressure drop characteristics of the cryogenic liquid oxygen propellant counterflowing in the cooling channel of the DemoP1 aerospike engine demonstrator.

The primary output data from the optical profilometry measurements on the Additively Manufactured (AM) sample of the DemoP1 aerospike engine demonstrator is an evaluation profile for the heights distribution of the irregular rough elements of the sample. In addition, experimental measurements regarding the statistical surface roughness parameters of the arithmetic mean deviation (R_a), the Root-Mean-Square roughness (R_q) and the maximum peak to valley height of the evaluation profile (R_z) are obtained. The experimentally measured values for the investigated statistical surface roughness parameters R_a , R_q and R_z are 9.28, 11.45 and 49.89 μm , respectively. In Fig. 21, a schematic representation of the mean line, in addition to the experimentally measured statistical surface roughness parameters R_a and R_q obtained from the optical profilometry process on the AM sample of the DemoP1 aerospike engine demonstrator, are presented. The mean line of the evaluation profile, defined as the mean surface height of the irregular rough elements is estimated to be at -0.82 μm , which is located slightly below the 0 μm value. In the case of the experimentally measured R_a and R_q statistical surface roughness parameters obtained from the results of the optical profilometry process, the origin for their schematic representation is the computed mean line of the evaluation profile.

For the characterisation of the evaluation profile for the roughness heights distribution in the Additively Manufactured (AM) sample of the DemoP1 aerospike engine demonstrator, the statistical surface roughness parameters for the arithmetic mean deviation R_a , Root-Mean-Square roughness R_q , maximum valley depth below the mean line R_v , maximum peak height above the mean line R_p , maximum peak to valley height R_z , skewness s_k and kurtosis k_u , can now be numerically estimated based on the definition of the discrete formulations presented in Table A.3. The computed values for the statistical surface roughness parameters of the evaluation profile exhibited in Fig. 21 are reported in Table A.4.

Table A.4

Statistical surface roughness parameters for evaluation profile of Additively Manufactured sample.

Parameter	Definition	Computed value
m	Mean line	-0.82 μm
R_a	Arithmetic mean deviation	9.57 μm
R_q	Root-Mean-Square roughness	12.18 μm
R_v	Maximum valley depth below mean line	35.13 μm
R_p	Maximum peak height above mean line	39.88 μm
R_z	Maximum peak to valley height	75.00 μm
s_k	Skewness	0.11
k_u	Kurtosis	3.35

Table A.5

Statistical surface roughness parameters based on experimental and computed data.

Parameter	Optical profilometry μm	Leach [60] μm	Error
R_a	9.28	9.57	3.12%
R_q	11.45	12.18	6.34%
R_z	49.89	75.00	50.34%

Following the numerical estimation of the statistical surface roughness parameters for the arithmetic mean deviation (R_a), the Root-Mean-Square roughness (R_q) and the maximum peak to valley height of the profile (R_z) of the evaluation profile in Fig. 21 based on the discrete formulations provided from Leach [60], the results can now be compared to the corresponding values obtained by means of the optical profilometry process on the AM sample of the DemoP1 aerospike engine demonstrator. The numerically and the experimentally determined values of the R_a , R_q and R_z statistical surface roughness parameters, in addition to the percentage deviation estimation resulted between the two approaches, are reported in Table A.5. It is shown that the percentage deviation between the numerical and experimental estimation of the arithmetic mean deviation R_a is 3.12%, whilst the corresponding error for the estimation of the Root-Mean-Square roughness R_q is 6.34%. Both percentage error estimations are considered within an acceptable range. However, in the case of the maximum peak to valley height of the statistical surface roughness parameter R_z , the percentage deviation between the numerically and the experimentally measured value on the Additively Manufactured (AM) sample of the DemoP1 aerospike engine demonstrator is approximately 50%. Note that large deviations between computations and experimental measurements of the R_z statistical surface roughness parameter have been reported in a previous experimental investigation of Stimpson et al. [31]. In their work, the authors state the limitations of the optical profilometry processes with

Table A.6

Roughness parameters for determination of equivalent sand-grain roughness height for evaluation profile of Additively Manufactured sample.

Parameter	Definition	Computed value [μm]
m	Mean line	−0.82
R_p	Maximum peak height above mean line	39.88
F_p	Floor profile	−10.11
F_d	Distance of floor profile from mean line	9.29
k_s	Equivalent sand-grain roughness height	49.17

respect to the quantitative information they provide on the surface structure of metallic samples fabricated using additive manufacturing techniques. Hence, large uncertainty is expected in the experimental determination of the R_z statistical parameter when optical profilometry processes are employed for the investigation of a metallic sample and as a result, a large variation between the numerical and the experimental estimation of the R_z parameter is anticipated.

The optical profilometry data obtained from the experimental investigation on the Additively Manufactured (AM) metallic sample of the DemoP1 aerospike engine demonstrator are used to quantify the equivalent sand-grain roughness height of the microfluidic cooling channel wall boundaries surfaces. The conceptualisation of the equivalent sand-grain roughness height originates from the work of Schlichting [61] and Nikuradse [62], however it is the work of Colebrook and White [63] which established the definition of the equivalent sand-grain roughness height k_s for the characterisation of irregular, non-uniform rough surfaces. A review of the approaches and correlations that can be employed for the determination of the equivalent sand-grain roughness height can be found in [57]. In the present numerical investigation for the characterisation of the cryogenic liquid oxygen coolant in the AM cooling channel of the aerospike engine, the estimation of the equivalent sand-grain roughness height k_s is based on work available in the literature [55,64]. The mean line of the evaluation profile, in addition to the statistical surface roughness parameter R_p representing the maximum peak height above the mean line are required for the numerical methodology of Brackbill and Kandlikar [55] and reported in Table A.4. The mean line of the evaluation profile has been determined as −0.82 [μm], whilst the R_p statistical surface roughness parameter has been estimated as 39.88 [μm]. In their work, Brackbill and Kandlikar [55] introduce the surface roughness parameter called “floor profile” F_p defined as the average height of all the rough elements that fall below the computed mean line of the sample evaluation profile, the distance F_d of the floor profile from the mean line parameter and ultimately the roughness height, k_s . The statistical surface roughness parameters required are determined as follows

$$F_p = \frac{1}{n} \sum_{i=1}^n z_i, \quad F_d = m - F_p \quad \text{and} \quad k_s = R_p + F_d, \quad (15)$$

where z_i denotes the roughness height of the rough elements located below the mean line of the evaluation profile, m , n is the total number of surface points and k_s the roughness height of the investigated Additive Manufactured (AM) sample of the DemoP1 aerospike engine demonstrator, obtained as the sum of the distance of the floor profile from the mean line F_d , and the maximum peak height above the mean line, R_p . At the wall boundaries of the Additively Manufactured (AM) cooling channel of the DemoP1 aerospike engine demonstrator, the value of the surface roughness is set equal to the equivalent sand-grain roughness height, k_s . The numerical value of the equivalent sand-grain roughness height imposed is determined based on the evaluated roughness height k_s (see Eq. (15)), with respect to the evaluation profile of the AM metallic sample exhibited in Fig. 21.

Therefore, in the present investigation, the roughness profile per se is not incorporated in the implemented numerical model. Instead, the aforementioned approach is implemented, relying on the determination of several statistical surface roughness parameters are determined. As

discussed, these statistical parameters are estimated based on the rough elements distribution of the evaluation profile. Then, the roughness height of the solid material wall boundaries of the numerical model is estimated, based on an approach suggested by Brackbill and Kandlikar [55]. The roughness height is then incorporated in the numerical model as a single value, characterising the roughness profile of the wall boundaries. The equivalent sand-grain roughness height is ultimately estimated as $k_s = 49.17$ [μm]. A review of the computed roughness parameters estimated in the numerical approach proposed by Brackbill and Kandlikar [55] is reported in Table A.6.

Data availability

Data will be made available on request.

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Monokrousos, Nikos; Könözy, László Z.; Pachidis, Vassilios; Sozio, Ernesto; Rossi, Federico

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