Data Article

Dataset of the experimentally measured heat transfer in the throat region of liquid rocket engine thrust chambers

Marco Pizzarelli

Italian Space Agency, Via del Politecnico snc, Rome 00133, Italy

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About 500 experimental heat transfer data taken from the open literature and relevant to the most thermally solicited area (i.e., the throat region) of liquid rocket engine thrust chambers, are collected and manipulated. This collection is the outcome of a thorough and exhaustive survey of the available experimental data of hot-fire tests produced to date. Among the test cases reported in the literature, only those with a throat heat transfer that is not affected by laminar flow, evident soot deposition, or intended non-uniform propellant injection are collected. The heat transfer is typically measured in terms of wall heat flux and temperature. Sometimes the heat transfer coefficient, which is a combination of these two terms, is provided. Each collected heat transfer measurement is supplied with data relevant to the specific operative condition of the considered test case, as well as the configuration of the adopted thrust chamber and propellant injector. Among the different considered propellant combinations, most of the experiments are made burning oxygen-hydrogen or oxygen-kerosene. Experiments made using mildly heated and compressed air, although not a rocket propellant, are also considered because of their relevance to the problem of interest. The collected dataset, called the primary dataset, is numerically elaborated to create a secondary dataset that is more thorough and consistent than the primary one. In fact, also thanks to the adoption of a suitable

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* Corresponding author.
E-mail address: marco.pizzarelli@asi.it

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hot-gas flow modeling, the secondary dataset contains elaborated data that are not always available in the selected open-literature as well as the non-dimensional numbers that are associated with the heat transfer and are typically used in regression rules, like the Nusselt and the Stanton numbers. The datasets presented in this manuscript are discussed and used to find heat transfer regressions in the research manuscript “Overview and analysis of the experimentally measured throat heat transfer in liquid rocket engine thrust chambers”, Acta Astronaut. 184 (2021), 46-58 [1].

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| Specifications Table |
|-----------------------|
| Subject               | Aerospace Engineering |
| Specific subject area | Liquid rocket engine; experimental hot-gas side heat transfer |
| Type of data          | Tables of primary and secondary data in spreadsheets |
| How data were acquired| Primary data: experimental data taken from the technical and scientific open literature. Data are typically extracted from tables and by the digitization of graphs. Secondary data: numerical elaboration of primary data, also by using the software CEA (Chemical Equilibrium with Applications) [2,3], which calculates chemical equilibrium compositions and properties of complex mixtures. |
| Data format           | Primary data: raw (with minimum algebraic manipulation to homogenize data coming from different literature sources). Secondary data: analyzed. |
| Parameters for data collection | Among the liquid rocket engine heat transfer experiments presented in the open literature, only those providing a direct measurement of the throat heat transfer and that are not affected by laminar flow, evident soot deposition, or intended non-uniform propellant injection are collected. |
| Description of data collection | Primary data: for each selected experiment, the main data reported are: the type of thrust chamber and injector; the most salient geometric parameters of the thrust chamber profile; the temperature, mass flow rate, and mixture ratio of the injected propellants; the chamber pressure; and the throat heat transfer. Note that, because each experimental test campaign is performed by a different research team, rarely all the information listed above is available. Secondary data: for each selected experiment, the main data reported are: the missing primary data; and the non-dimensional numbers associated with the heat transfer. |
| Data source location | Primary data sources: the bibliographic references of the technical and scientific open literature from which the primary data are extracted are provided in the spreadsheets containing the whole data collection. |
| Data accessibility    | Spreadsheets of the primary and secondary datasets are available as a supplementary material of this article. |
| Related research article | Marco Pizzarelli, Overview and analysis of the experimentally measured throat heat transfer in liquid rocket engine thrust chambers, Acta Astronaut. 184 (2021), 46-58 [1] |

Value of the Data

• The datasets provided are important because they potentially contain all the experimental data present in the open literature on the heat transfer in the throat region of liquid rocket engine thrust chambers.
• Both designers, experimenters, and theoretical researchers interested in liquid rocket engine thrust chambers can benefit from the provided datasets.
• The datasets provided can be used: by designers to estimate the throat heat transfer, which is one of the most decisive parameters for the correct thermo-structural dimensioning of a thrust chamber; by experimenters to replicate data acquired in the past by different research teams or to investigate the heat transfer in unexplored operating conditions and using new thrust chamber and injector configurations; and by theoretical researchers to calibrate or compare their rocket heat transfer models.

1. Data Description

1.1. Primary dataset spreadsheet

For each collected experiment, the primary dataset spreadsheet contains the information on the type of thrust chamber and injector tested, the available data pertinent to the geometry of the thrust chamber profile (diameter, length, radius of curvature, convergent angle, and characteristic length), the temperature, mass flow rate, and mixture ratio of the injected propellants, the characteristic velocity or combustion efficiency (only if the propellant mass flow rate is not available), the chamber pressure, and the throat section heat transfer data. These latter data, depending on what is reported in the literature sources, are the wall temperature and/or the heat flux, and/or the heat transfer coefficient. For some experiments, two heat transfer data are reported. This occurs when multiple spatial or temporal measures are available at the throat section. The two reported values represent the minimum and maximum heat transfer values. Notes on how the propellant mass flow rate and the heat transfer were measured or calculated by the authors of the literature sources are also reported in the spreadsheet. The data in the spreadsheet are divided into three main groups named bi-propellant, tri-propellant, and air. The first group, containing the majority of the data, is pertinent to thrust chambers operating with one oxidizer and one fuel. Examples of propellant pairs are: O2-H2, O2-kerosene, N2O4-N2H4, etc. The second group contains the data coming from a thrust chamber operating with F2, H2, and Li as propellants. Finally, the third group contains the data coming from experiments carried out using heated air as working fluid. For each of the main groups, the data originated from the same experimental test campaign are grouped together in such a way as to have homogeneous data in terms of propellants used, type and dimensions of the thrust chamber, measuring techniques, etc. Note that, because each experimental test campaign is performed by a different research team, rarely all the information listed above is provided in the literature sources.

1.2. Secondary data spreadsheet

The secondary dataset spreadsheet contains all the information already present in the primary dataset spreadsheet and those that are missing. To estimate the latter, suitable assumptions are made. For instance, a simplified model of the thrust chamber profile is used to estimate the missing geometric parameters. When the mass flow rate is not provided as primary data, it can be computed from the original value of the combustion efficiency or the characteristic velocity. However, there are some cases where both the mass flow rate, the combustion efficiency, and the characteristic velocity are missing in the literature sources. In such cases, the mass flow rate is computed by assuming a value (or a range of values) for the combustion efficiency. Concerning the throat wall temperature, if it is not provided as primary data, it is computed from the available value of the heat transfer coefficient and the heat flux. If the wall temperature is not provided, nor can it be computed, a minimum and a maximum value are assumed. Similarly, when the throat heat flux is not provided in the original reference, it is computed from the available values of the heat transfer coefficient and the wall temperature. The spreadsheet of
the secondary dataset contains also the computed values of the non-dimensional numbers to be used in regression rules for the heat transfer, that are, the throat Reynolds, Prandtl, Nusselt, and Stanton numbers. The spreadsheet is completed with some notes clarifying whether the mass flow rate, the wall temperature, and the heat fluxes are provided in the literature sources. If not, it is indicated how these values are computed or estimated. Similarly to the primary data spreadsheet, the secondary data spreadsheet is divided into three main groups (bi-propellant, tri-propellant, and air) and the data coming from the same experimental test campaign are grouped together.

2. Experimental design, Materials and Methods

2.1. Primary dataset: criteria for selecting the experiments of interest

Among the experiments found in the open literature and containing measurements of throat heat transfer, only those satisfying the following conditions are selected: (i) turbulent flow; (ii) no evident soot deposition; (iii) uniform injection. The identification of these conditions is not always straightforward. Therefore, the selected experiments may partially not satisfy the three conditions listed above. In any case, all the reported data are associated to steady-state heat transfer. In what follows, a methodological discussion on how the experiments have been selected is given. For what regards conditions (i), data with Reynolds number below about 200,000 are discarded. In fact, below a throat Reynolds number of 200,000 the flow is typically laminar while in the range between 200,000 and 400,000 the flow may be laminar, transitional, or turbulent, depending on throat chamber geometry and combustion effects [4]. For what regards conditions (ii), to avoid the inclusion of heat transfer data affected by solid carbon (i.e., soot) deposition, only experiments that didn’t show visual evidence of carbon buildup during the post-test inspection and with stable heat flux with time are taken. In fact, when soot is present, the heat flux decreases with time as a result of the increasing thickness of the carbon deposition at the wall. Finally, to respect condition (iii), test cases with film cooling or intended non-uniform injection (e.g., propellant mixture ratio bias) that affect the throat heat transfer are discarded. Such injection configurations are sometimes easily identifiable as the heat transfer with and without uniform injection has been compared in some test campaigns. With the above-described logic, a total number of 488 experiments are selected.

2.2. Secondary dataset: evaluation of the thrust chamber geometric parameters

A sketch of a thrust chamber inner contour with relevant geometric parameters that may have an impact on the heat transfer, especially in the throat region, is presented in Fig. 1. These parameters are the cylinder length \( L_{cyl} \), the convergent length \( L_{con} \), the cylinder diameter \( D_{cyl} \), the throat diameter \( D_t \), the radius of curvature just upstream the throat \( R_c \), and the convergent angle \( \theta_c \). Other notable geometric parameters are the contraction ratio \( \varepsilon_c = \frac{A_{cyl}}{A_t} \), where \( A_{cyl} \) and \( A_t \) are the cylinder and the throat cross-section area, respectively, and the characteristic length \( L^* = \frac{V_c}{A_t} \), where \( V_c \) is the thrust chamber volume from the injector plate to the throat section. All these parameters are reported in the spreadsheet of the secondary dataset. To estimate the geometric data that are often missing in the literature sources, the simplifying hypothesis of considering the convergent as a truncated cone with a slope equal to \( \theta_c \) is made. Consequently, the characteristic length and the convergent length are approximated as:

\[
L^* = \varepsilon_c L_{cyl} + D_t \frac{\varepsilon_c^{1.5} - 1}{6 \tan(\theta_c)} \quad L_{con} = D_t \frac{\varepsilon_c^{0.5} - 1}{2 \tan(\theta_c)}
\]

With these relations it is possible to estimate, for instance, \( L^* \) and \( \theta_c \) if \( D_{cyl}, D_t, L_{cyl}, \) and \( L_{con} \) are known. Viceversa, it is possible to estimate \( L_{cyl} \) and \( L_{con} \) if \( D_{cyl}, D_t, L^*, \) and \( \theta_c \) are known. Note
that, on the other hand, the radius of curvature $R_c$ cannot be approximated in any way, and thus it is often missing also in the spreadsheet of the secondary dataset.

2.3. Secondary dataset: evaluation of the non-dimensional numbers

The heat transfer within liquid rocket engines is typically described by the Nusselt ($Nu$) or the Stanton ($St$) number as a function of the Reynolds ($Re$) and the Prandtl ($Pr$) numbers [1]. These non-dimensional numbers are defined as:

$$
Re = \frac{\rho u D}{\mu}, \quad Pr = \frac{\mu c_p}{k}, \quad Nu = \frac{h_{g,T} D}{k}, \quad St = \frac{h_{g,i}}{\rho u}
$$

(2)

where $u$, $\rho$, $c_p$, $\mu$, $k$ are the hot-gas velocity, density, specific heat at constant pressure, viscosity, and thermal conductivity, respectively. $D$ is the thrust chamber cross-section diameter. It is indicated as $D_t$ when considering the throat section (Fig. 1). The temperature-based heat transfer coefficient ($h_{g,T}$) and the enthalpy-based heat transfer coefficient ($h_{g,i}$) are defined as:

$$
h_{g,T} = \frac{q_w}{T_{aw} - T_w}, \quad h_{g,i} = \frac{q_w}{i_{aw} - i_w}
$$

(3)

where $T_w$ and $i_w$ are the hot-gas temperature and enthalpy at the wall, respectively, and $q_w$ is the hot-gas side wall heat flux. The adiabatic wall variables $T_{aw}$ and $i_{aw}$ represent the hot-gas temperature and enthalpy at the wall in case of adiabatic flow. Because of the large hot-gas temperature variations across the boundary layer and the chemically reacting flow behavior, the definition of a reference state to evaluate the hot-gas variables $\rho$, $c_p$, $\mu$, and $k$ is not straightforward. To this aim, a reference enthalpy based on Eckert’s method is often adopted [5]. Eckert’s reference enthalpy is an average of the free-stream, the wall, and the adiabatic wall enthalpies ($i$, $i_w$, and $i_{aw}$, respectively): $i_{ref} = 0.28 i + 0.5 i_w + 0.22 i_{aw}$ where $i_{aw}$ in case of turbulent flow is evaluated as $i_{aw} = i + Pr^{1/3}(i_0 - i)$. The Eckert’s reference state changes according to the hypothesis on the chemical reactivity of the hot-gas near the wall. Three different approaches of increasing complexity are considered to evaluate the non-dimensional numbers $Nu$ or $St$, $Re$, and $Pr$: (a) hot-gas properties evaluated at the free-stream state, that is, outside the boundary layer; (b) hot-gas properties evaluated at the Eckert’s reference state considering frozen chemical composition in the boundary layer; and (c) hot-gas properties evaluated at the Eckert’s reference state considering chemical equilibrium in the boundary layer. All three of these approaches are
based on the same input data coming from the experimental measurements: the combustion chamber pressure $p_0$, the oxidizer-to-fuel mass mixture ratio $o/f$, the characteristic velocity $c^*$, and the hot-gas side wall heat flux $q_w$ and wall temperature $T_w$. For what concerns the evaluation of the characteristic velocity $c^*$, it is computed as $c^* = p_0 A_t / \dot{m}$ if the experimental data of the propellant mass flow rate $\dot{m}$ is available. Otherwise, if the combustion efficiency $\eta_{c^*}$ is known or it is properly estimated, the characteristic velocity is computed as $c^* = \eta_{c^*} c_{id}^*$ where $c_{id}^*$ is the ideal characteristic velocity. It is computed considering a one-dimensional isentropic expansion through the thrust chamber of the hot-gas in chemical equilibrium [2,3]. The input data for the evaluation of $c_{id}^*$ are $p_0$, $o/f$, and the inlet temperature of the propellant. Finally, for few cases the value of the characteristic velocity is provided directly in the original references. Details of the three calculation procedures to evaluate the relevant non-dimensional numbers are provided below for the case of interest, which is the throat region heat transfer. The turbulent boundary layer hypothesis is considered valid.

a) Formulation based on hot-gas properties evaluated at the free-stream state

A one-dimensional isentropic expansion from the inlet section, considered with an infinite area, up to the throat of the hot-gas in chemical equilibrium is computed considering the known values of $p_0$ and $o/f$, and a proper value of the propellant inlet enthalpy $i_0$ such to match the experimental value of $c^*$. The resulting hot-gas variables at the throat section ($u_{\infty}$, $\rho_{\infty}$, $c_p\rho_{\infty}$, $\mu_{\infty}$, and $k_{\infty}$) are used to evaluate the non-dimensional numbers $Nu_{\infty}$, $Re_{\infty}$, and $Pr_{\infty}$ according to Eq. 2. The subscript “∞” indicates that the hot-gas variables are the free-stream ones. The adiabatic wall temperature $T_{aw}$ to be used in the definition of $h_{g,f}$ (Eq. (3)) and thus in $Nu_{\infty}$ is estimated as $T_{aw} = T_{\infty} + Pr_{\infty}^{1/3} (T_0 - T_{\infty})$, where $T_{\infty}$ is the hot-gas free-stream temperature at the throat section and $T_0$ is the combustion chamber temperature. Note that this formulation has the great advantage, with respect to the following ones, of requiring minimum thermodynamic computations.

b) Formulation based on hot-gas properties evaluated at the Eckert’s reference state considering frozen chemical composition in the boundary layer

In this case, the hot-gas properties at the throat section are evaluated at a reference state defined by the pressure $p_{\infty}$ and the Eckert’s reference enthalpy $i_{ref} = 0.5(i_{\infty} + i_w) + 0.22Pr_{\infty}^{1/3} (i_0 - i_{\infty})$. Note that the properties $p_{\infty}$, $i_{\infty}$, and $Pr_{\infty}$ are the throat free-stream properties, $i_0$ is the propellant inlet enthalpy, all evaluated as indicated in the formulation a) (that is, considering the free-stream in chemical equilibrium). The enthalpy $i_w$ is the hot-gas enthalpy evaluated at the throat free-stream pressure $p_{\infty}$ and wall temperature $T_w$ and considering that the hot-gas composition is equal to the free-stream one (i.e., frozen chemical composition). The hot-gas properties that are associated with $p_{\infty}$, $i_{ref}$, and frozen chemical composition are $\rho_f$, $c_p\rho_f$, $\mu_f$, and $k_f$. The subscript “f” emphasizes that the hot-gas is considered at frozen chemical composition in the boundary layer. The non-dimensional numbers evaluated according to Eq. 2 are $St_f$, $Re_f$, and $Pr_f$. Note that the hot-gas velocity to be used in the definition of $St_f$ and $Re_f$ is the free-stream one ($u_{\infty}$), as evaluated in the formulation a), and that the adiabatic wall enthalpy $i_{aw}$ to be used in the definition of $h_{g,i}$ (Eq. (3)), and thus in $St_f$, is estimated as $i_{aw} = i_f + Pr_{\infty}^{1/3} (i_0 - i_f)$.

c) Formulation based on hot-gas properties evaluated at the Eckert’s reference state considering chemical equilibrium in the boundary layer

This approach is similar to the previous one but the hot-gas is considered in chemical equilibrium also in the boundary layer. In particular, the hot-gas properties at the throat section are still evaluated at a reference state defined by the pressure $p_{\infty}$ and the Eckert’s reference enthalpy $i_{ref} = 0.5(i_{\infty} + i_w) + 0.22Pr_{\infty}^{1/3} (i_0 - i_{\infty})$ but the wall enthalpy $i_w$ is now evaluated considering that the hot-gas composition is in chemical equilibrium. Chemical equilibrium condition at the throat free-stream pressure $p_{\infty}$ and the reference enthalpy $i_{ref}$ is also imposed to evaluate the hot-gas reference variables $\rho_e$, $c_p\rho_e$, $\mu_e$, and $k_e$ and consequently, according to Eq. 2, the non-dimensional numbers $St_e$, $Re_e$, and $Pr_e$. The subscript “e” indicates that the hot-gas is
considered in chemical equilibrium. Also for this formulation, the hot-gas velocity to be used in the definition of $St_e$ and $Re_e$ is the free-stream one ($u_\infty$), as evaluated in the formulation a), and the adiabatic wall enthalpy $i_{aw}$ to be used in the definition of $h_{g,i}$ (Eq. (3)), and thus in $St_e$, is estimated as $i_{aw} = i_e + Pr_e^{1/3}(i_0 - i_e)$.

**Ethics Statement**

The author declares that he has followed the general ethics rules of scientific research performance and publishing.

**CRediT Author Statement**

**Marco Pizzarelli:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing.

**Declaration of Competing Interest**

The author declares that he has no known competing financial interests or personal relationships which have, or could be perceived to have, influenced the work reported in this article.

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**Supplementary Materials**

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.dib.2021.107173

**References**

[1] M. Pizzarelli, Overview and analysis of the experimentally measured throat heat transfer in liquid rocket engine thrust chambers, Acta Astronaut. 184 (2021) 46–58, doi:10.1016/j.actaastro.2021.03.028.

[2] S. Gordon, B.J. McBride, Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications (I. Analysis), report, National Aeronautics and Space Administration, NASA, 1994, Contract RTOP 505-62-52

[3] S. Gordon, B.J. McBride, Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications (II. Users Manual and Program Description), report, National Aeronautics and Space Administration, NASA, 1996, Contract RTOP 505-62-52

[4] L. Schoenman, P. Block, Laminar boundary-layer heat transfer in low-thrust rocket nozzles, J. Spacecraf. Rocket. 5 (9) (1968) 1082–1089, doi:10.2514/3.29425.

[5] E.R.G. Eckert, Survey on Heat Transfer at High Speeds, report, Wright Air Development Center, United States Air Force, 1954.