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Experimental evidence of the impact of radiation coupling on binary scaling applied to shock layer flows

G. de Crombrugghe [a,*], O. Chazot [b], T.J. McIntyre [c], R. Morgan [a]

[a] Centre for Hypersonics, The University of Queensland, Brisbane 4072, Australia
[b] von Karman Institute, Sint-Genesius-Rode 1640, Belgium
[c] School of Mathematics and Physics, The University of Queensland, Brisbane 4072, Australia

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ABSTRACT

Binary scaling is a similitude law used to study the aerothermodynamics of hypersonic vehicles in ground-based high-enthalpy facilities. It enables the duplication of shock layer flows in the vicinity of the stagnation point, including binary chemistry and nonequilibrium processes, over length scales that are practical for experimental testing. It is built on the assumption of a flow devoid of radiation coupling, which drastically narrows down the envelope of flows for which binary scaling can be used. Indeed, if it is strong enough, radiative heat transfer will cause a substantial amount of energy to leak out of the shock layer to the free-stream and other flow regions. As demonstrated in this paper, the strength of that coupling will increase as the length-scale of the flow increases, impacting other flow properties such as its chemical composition or temperature. The resulting impact on macroscopic features of the flow are for example a reduction of the wall heat flux (both convective and radiative) or of the shock standoff distance. These side impacts are identified with experimental measurements on the shock standoff distance in an expansion tube with CO_2—N_2 mixture flows representative of the venusian atmosphere over cylinders.

1. Introduction

The binary scaling law aims to create partial similarity between a laboratory flow and hypersonic flight. It states that flows with the same gas composition, free-stream enthalpy h_∞, and product of a density and a length-scale ρL will be characterised by the same binary chemistry, nonequilibrium processes, and diffusive transport [1] over proportional length-scales. Binary scaling was originally suggested by Birkhoff [2] and later refined by numerous authors, who notably identified the fractional extent of the nonequilibrium region as a key characteristic driving its applicability [3–6]. Despite its known limitations, it is commonly used as a scaling parameter to duplicate extreme hypersonic flow conditions (e.g. super-orbital entry) in high-enthalpy facilities (see for example [6–12]).

One of these limitations is radiative coupling. Gases radiate a portion of their energy when they are brought up to sufficiently high temperatures, as it is typically the case for atmospheric entry. It results both in energy losses, through emission in hot parts of the flowfield, and energy gain, through absorption in colder parts of the flowfield. As a result, the gas-phase of the flow is not adiabatic. The intensity of this coupling is characterised with the Goulard number [13] which, as it will be demonstrated in this paper, is not duplicated within a family of binary scaled flows. Consequently, the spatial distribution of enthalpy varies depending on the length-scale of the flow, further impacting macroscopic flow properties. The applicability of binary scaling does henceforth also depend on the parameters driving radiation coupling.

This result is verified experimentally measuring the shock standoff over cylinders in three flows that are similar from the binary scaling point of view, but that present different level of radiation coupling (i.e. different Goulard numbers). In this paper, we first demonstrate analytically that the strength of the radiative coupling increases with the length-scale of the flow. We then present the three flows used in this test campaign, along with a preliminary estimation of the shock standoff distance based on some of the most widely used correlations. We then describe the experimental technique used to quantify the dimensionless shock standoff, and present the associated results. These indicate that the dimensionless shock standoff does indeed shrink as the length-scale of the flow is reduced. This allows us to confirm that, within

* Corresponding author.
E-mail address: g.crombrugg@gmail.com (G. de Crombrugghe).

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Nomenclature

Roman symbols

A	area [m^2]
c_p	heat capacity at constant pressure [J/K]
D	diameter [m]
E	energy [J]
h	specific enthalpy [J/kg]
I	irradiance *or* radiance [W/m^2]
L	length [m]
m	mass [kg]
q	heat flux [W/m^2]
R	radius [m]
t	time [s]
T	temperature [K]
v	velocity [m/s]
y	direction of space [m]

Greek symbols

Γ	Goulard number [–]
ϵ	error [–]
Δ	shock stand-off distance [m]
η	emission coefficient [W/m^3]
κ	absorption coefficient [/m]
ν	frequency [Hz]
ρ	density [kg/m^3]
σ	standard deviation
χ	scale factor [–]
ω	solid angle [sr]
$\tilde{\Omega}$	Damkhöler number [–]

Sub- and Superscripts

ad	adiabatic
lab	flow in the laboratory (down-scale)
meas	on a single measurement
s	sensible
set	on a set of measurements
∞	free-stream

a family of binary scaled flows, radiation coupling causes the shock layer temperature to decrease with the length-scale of the flow.

2. Radiatively coupled shock layer flows under binary scaling conditions

Let us consider the amount of radiative energy dE in the frequency interval $\nu, \nu + d\nu$ going across the surface area dA during a time dt in all directions formed by the solid angle $d\omega$ around a direction r perpendicular to that surface and going through a point P belonging to it. The specific radiative intensity I_ν is then, at P, the radiative energy transferred in the direction r per unit of frequency, per steradian (unit of solid angle), per unit of time:

$$I_\nu \equiv \lim_{d\nu, dA, d\omega, dt \to 0} \left(\frac{dE}{d\nu \cdot dA \cdot d\omega \cdot dt} \right) \quad (1)$$

The integrated radiative intensity I is simply obtained as:

$$I = \int_0^\infty I_\nu d\nu \quad (2)$$

And the radiative heat flux q, i.e. the net flux of radiative energy across a surface per unit of time, is:

$$q = \int \frac{dE}{dAdt} = \int_0^{4\pi} I \cos\theta d\omega \quad (3)$$

The rate of change of I_ν along the direction y can thus be expressed as:

$$\frac{dI_\nu}{dy} = \eta_\nu - \kappa_\nu I_\nu \quad (4)$$

The emission coefficient η and absorption coefficient κ are not intrinsic properties of the mixture but rather depend in a linear fashion on its density through the number density. They can thus be replaced by their specific version (in terms of mass): κ_ρ, σ_ρ, and τ_ρ. Eq. (4) can thus be written as:

$$dI_\nu = \rho \eta_{\rho,\nu} dy - \rho \kappa_{\rho,\nu} I_\nu dy \quad (5)$$

Hence, the radiative intensity scales as ρL (i.e. ρdy) and is thus preserved through binary scaling. Solid angles being dimensionless, it follows from Eq. (3) that the radiative heat flux is also preserved. This result is fundamental, as it implies that a specific point in the flow will radiate and receive the same intensity no matter what the scale of the flow is.

However, from Eq. (3), the amount of energy E radiated over the whole spectrum through an area dA located in P in the interval of time dt is obtained as:

$$dE = I \cos\theta dA d\omega dt \quad (6)$$

which implies that the amount of energy radiated by a control volume scales as ρL^3 (i.e. IdA). In other words, it is proportional to the mass contained in that volume. However, the flux of mass into the shock layer scales as:

$$d\dot{m} = \rho_\infty v_\infty dA \quad (7)$$

As a result, the amount of heat radiated per unit of mass ingested in the shock layer scales as:

$$\frac{dE}{d\dot{m}} \propto \frac{\rho L^3}{\rho L^2} = L \quad (8)$$

Therefore, the heat radiated by a fluid element in the shock layer in the facility is smaller than that radiated by a scaled fluid element in flight.

The non-adiabaticity only poses a problem if the radiative heating is important enough to have an influence on the rest of the flowfield. Goulard presented a useful tool to estimate the extent of that coupling, based on an analytical solution of the incompressible shock layer in which radiation losses are considered as a perturbation to the exact adiabatic solution [13]. With the development of CFD, the adiabatic heat flux q_{ad} can now be estimated and the Goulard number is thus better known in the literature (see for example [14–16]) under the following form:

$$\Gamma = \frac{2 q_{ad}}{\frac{1}{2} \rho_\infty v_\infty^3} \quad (9)$$

If Γ is small, which is the case for most ballistic and orbital entry problems, the total temperature can be considered constant along the stagnation line. If Γ is large, heat loss through radiation becomes important and the radiation term has to be included in the Navier-Stokes equation for the conservation of energy.