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Gas film/regenerative composite cooling characteristics of the liquid oxygen/liquid methane (LOX/LCH4) rocket engine

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S1 Schematic diagram of thrust chamber heat transfer process

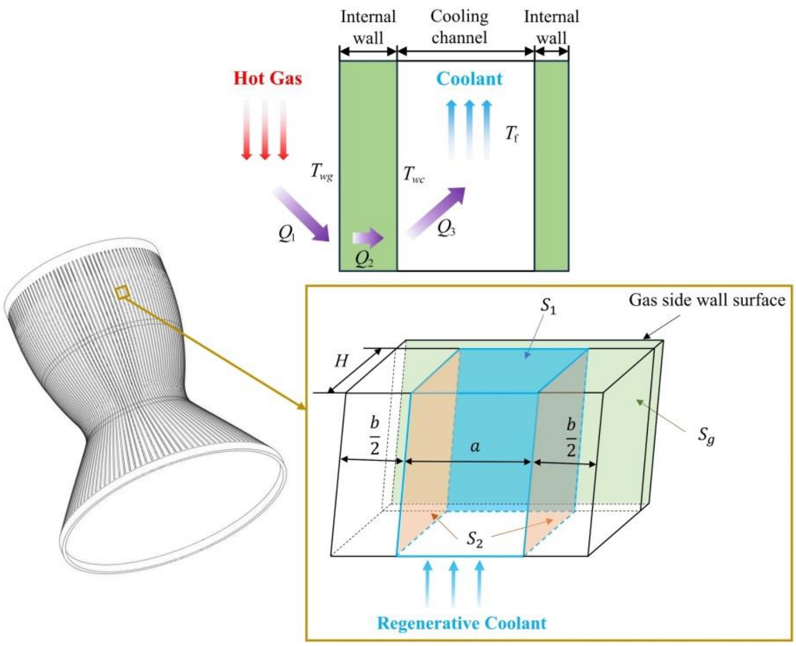

Fig. S1 Schematic diagram of thrust chamber heat transfer process

S2 Expression of semi-empirical Bartz formula

$$h_{\mathrm{g}}=\left(\frac{A_{\mathrm{t}}}{A}\right)^{0.9}\sigma_{\mathrm{cf}}\times\left[\frac{0.026}{D_{\mathrm{t}}^{0.2}}\left(\frac{\mu_{\mathrm{g}}^{0.2}c_{p,\mathrm{g}}}{Pr^{0.6}}\right)_{\mathrm{ns}}\left(\frac{(p_{\mathrm{c}})_{\mathrm{ns}}}{c^{*}}\right)^{0.8}\left(\frac{D_{\mathrm{t}}}{R}\right)^{0.1}\right], \tag{S1}$$

$$\sigma_{\mathrm{cf}}=\left(1+\frac{\gamma-1}{2}Ma_x^2\right)^{-0.12}\times\left[\frac{1}{2}\frac{T_{\mathrm{wg}}}{(T_{\mathrm{c}})_{\mathrm{ns}}}\left(1+\frac{\gamma-1}{2}Ma_x^2\right)+\frac{1}{2}\right]^{-0.68}. \tag{S2}$$

D_{t} is the throat diameter. μ_{g} is the gas dynamic viscosity. $c_{p,\mathrm{g}}$ is the gas specific heat at constant pressure. Pr is the gas Prandtl number. c^{*} is the gas characteristic velocity. σ_{cf} is the correction factor for property variations across the boundary layer. R is the radius of curvature of nozzle contour at throat. A_{t} is the throat area of the nozzle and A is the area under consideration along chamber axis. T_{wg} is the gas side wall temperature. T_c and p_c are respectively combustion temperature and pressure. The subscript 'ns' represents the stagnation parameter. γ is the specific heat ratio of the gas and Ma_x denotes the local Mach number.

S3 Expression of dimensionless numbers

$$Bo = \frac{q}{G_{\mathrm{f}} h_{\mathrm{fg}}}. \tag{S3}$$

$$We = \frac{G_{\mathrm{f}}^{2} D_{\mathrm{h}}}{\rho_{\mathrm{lp,f}} \sigma'}. \tag{S4}$$

$$K_{\mathrm{p}} = \frac{p}{\sigma' g(\rho_{\mathrm{lp,f}} - \rho_{\mathrm{gp,f}})^{0.5}}. \tag{S5}$$

$$X = (\frac{1-x}{x})^{0.9} (\frac{\rho_{\mathrm{gp,f}}}{\rho_{\mathrm{lp,f}}})^{0.5} (\frac{\mu_{\mathrm{gp,f}}}{\mu_{\mathrm{lp,f}}})^{0.1}. \tag{S6}$$

G_f is the coolant mass flow rate. D_h is the hydraulic diameter of cooling channel. σ' is the coefficient of surface tension. x is the mass quality. h_{fg} and q are respectively the coolant latent heat of evaporation and heat flux. μ, ρ and p are respectively dynamic viscosity, density and pressure. And the subscript 'gp', 'lp', 'f' represent gas-phase, liquid-phase and coolant, respectively.

S4 Expression of frictional pressure drop and acceleration pressure drop

(1) Single phase calculation

The calculation formula for frictional and acceleration pressure drop in the single-phase region is as follows:

$$\Delta p_{\mathrm{fr}} = f_{\mathrm{sp}} \cdot \frac{G_{\mathrm{f,sp}}^{2}}{2\rho_{\mathrm{sp}} D_{\mathrm{h}}} \cdot L. \tag{S7}$$

$$\Delta p_{\mathrm{ac}} = \frac{G_{\mathrm{f,sp}}^{2}}{2\rho_{\mathrm{sp,in}}} (\frac{\rho_{\mathrm{sp,in}}}{\rho_{\mathrm{sp,out}}} - 1). \tag{S8}$$

In the Eq. (S7) and (S8), the subscript 'sp' represents the single-phase parameters. $G_{f,sp}$ is the mass flow rate of the single-phase coolant. ρ_{sp} is the average density of the single-phase coolant, and $\rho_{sp,in}$ and $\rho_{sp,out}$ represent the inlet and outlet densities of the coolant, respectively. D_h is the hydraulic diameter of the coolant channel, and L is the length of the coolant channel. f_{sp} is the single-phase friction factor, which can be determined using the Colebrook formula:

$$\frac{1}{\sqrt{f_{\mathrm{sp}}}} = -2\log\left(\frac{Ra/D_{\mathrm{h}}}{3.7} + \frac{2.51}{Re\sqrt{f_{\mathrm{sp}}}}\right). \tag{S9}$$

Where the Ra is the regenerative cooling channel surface roughness.

(2) Two-phase calculation

In the two-phase region, a homogeneous model is used to calculate the frictional pressure drop:

$$\Delta p_{\mathrm{fr}} = f_{\mathrm{tp}} \frac{G_{\mathrm{f,tp}}^2}{2\rho_{\mathrm{tp}}} \frac{L}{D_{\mathrm{h}}}. \tag{S10}$$

In the Eq. (S10), the subscript 'tp' represents the two-phase parameters. $G_{\mathrm{f,tp}}$ is the mass flow rate of the two-phase coolant, ρ_{tp} is the average density of the two-phase coolant, and f_{tp} is the two-phase friction factor. The calculation formula for ρ_{tp} and f_{tp} is as follows.

$$\rho_{\mathrm{tp}} = \frac{\rho_{\mathrm{lp}}\rho_{\mathrm{gp}}}{\rho_{\mathrm{gp}}(1-x)+\rho_{\mathrm{lp}}x}. \tag{S11}$$

$$\frac{1}{\sqrt{f_{\mathrm{tp}}}} = -2\log\left(\frac{Ra/D_{\mathrm{h}}}{3.7} + \frac{2.51}{Re\sqrt{f_{\mathrm{tp}}}}\right). \tag{S12}$$

Where the ρ_{lp} and ρ_{gp} represent the densities of the liquid phase and gas phase coolant in the two-phase region, respectively. x is the coolant dryness fraction, and Ra is the regenerative cooling channel surface roughness.

The acceleration pressure drop can be expressed as follows:

$$\Delta p_{\mathrm{ac}} = G_{\mathrm{f,tp}}^2 L\left[\frac{(1-x)^2}{\rho_{\mathrm{lp}}(1-\varepsilon')} + \frac{x^2}{\rho_{\mathrm{gp}}\varepsilon'}\right]. \tag{S13}$$

Where the ε' is void fraction. The calculation formula for ε' is as follows:

$$\varepsilon' = \frac{\rho_{\mathrm{lp}}/\rho_{\mathrm{gp}}}{1/x+(\rho_{\mathrm{lp}}/\rho_{\mathrm{gp}}-1)}. \tag{S14}$$

S5 Different gas film mass flow comparison schemes

Table S1 Different gas film mass flow comparison schemes

Gas film mass flow rate	Gas film mass flow (kg/s)	Gas film introduction position	Gas film introduction coordinate (m)
10%	0.101	Thrust chamber head	$Z = 0$
15%	0.152	Thrust chamber head	$Z = 0$
20%	0.202	Thrust chamber head	$Z = 0$
25%	0.253	Thrust chamber head	$Z = 0$

S6 Comparison of different gas film introduction positions

Table S2 Comparison of different gas film introduction positions

Scheme	Gas film introduction position	Gas film introduction coordinate (m)	Gas film mass flow rate
case 1	head of the thrust chamber	$Z = 0$	20%

case 2	midpoint of the cylinder section	Z = 0.075	20%
case 3	starting point of the cylinder section	Z = 0.15	20%
case 4	midpoint of the convergence section	Z = 0.189	20%

S7 Comparison of double row hole schemes

Table S3 Comparison of double row hole schemes

Scheme	Coordinates of the first row of holes (m)	Flow rate of the first row of holes	Coordinates of the second row of holes (m)	Flow rate of the second row of holes
case 1	Z = 0	20%	/	/
case 5	Z = 0	10%	Z = 0.043	10%
case 6	Z = 0	10%	Z = 0.075	10%
case 7	Z = 0	10%	Z = 0.150	10%

S8 Nomenclature

Nomenclature

a	channel width, m
A	area
b	rib width, m
Bo	boiling number
c^*	characteristic velocity, m/s
c_p	specific heat at constant pressure, J/kg K
D	diameter, m
f	friction coefficient
g	gravitational acceleration, m/s^2
G	mass flow rate, kg/m^2 s
h	convective heat transfer coefficient, W/m^2 K
h_{fg}	latent heat of evaporation, kJ/kg
H	rib height, m
K_p	dimensionless pressure parameter
L	cooling channel length, m
$\dot{m}$	mass flow rate, kg/s
M	blowing ratio
Ma	Mach number of gas flow
MR	oxidizer to fuel mixture ratio
n	number of calculation nodes
N	number of regenerative cooling channels
Nu	Nusselt number
p	pressure, MPa
Δp_{fr}	frictional pressure drop, MPa
Δp_{lo}	local pressure drop, MPa
Δp_{gr}	acceleration pressure drop, MPa
Δp_{ac}	gravity pressure drop, MPa
Pr	Prandtl number
q	heat flux, W/m^2
R	Radius, m
Ra	surface roughness, μm
Re	Reynolds number
S_1	bottom surface areas of cooling channel, m^2
S_2	side surface areas of cooling channel, m^2
S_g	total surface area of the gas side wall, m^2
S_{tot}	the total rib surface area, m^2
T	temperature, K
Z	axial coordinates of thrust chamber, m
Z_{gf}	non-dimensional distance downstream of the cooling film
Z_{gf0}	non-dimensional location of the cooling film effective leading edge
δ	thickness, m
ρ	density, kg/m^3
μ	dynamic viscosity, Pa s
γ	specific heat ratio of gas
σ'	coefficient of surface tension
σ_{cf}	correction factor for property variations across the boundary layer
ε	nozzle expansion ratio
ε'	void fraction
λ	coefficient of thermal conductivity, W/m K
η	cooling efficiency

Subscripts

aw	adiabatic wall of gas-side
c	combustion chamber
co	coolant
f	coolant
fr	friction
g	mainstream gas
gp	gas-phase
h	hydraulic
i	inlet
lp	liquid-phase
max	maximum value
ns	stagnation parameter
p	propellant
rc	regenerative cooling channel
sp	single phase
t	throat
tp	two phase
w	wall of thrust chamber
wg	gas-side wall
0	initial condition of gas film

u	velocity, m/s
We	Weber number
x	dryness fraction
Δx	calculation step length, m
X	Martinelli number
z	distance from the gas film inlet, m

Acronyms

RCC	regenerative cooling channel
RPL	rated power level
HTD	heat transfer deterioration
LPV	local peak value