Study of Film Cooling in Diverging Section of Nuclear Rocket Nozzle

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INTRODUCTION

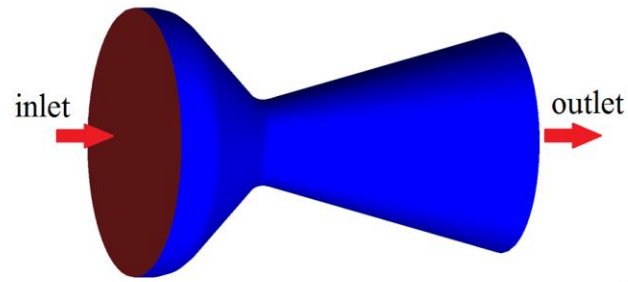
The future direction of manned space exploration is dependent on decreasing launch costs relative to modern day chemically-fueled rocket. The high scientific and technological level of atomic power engineering made it available to use nuclear energy reactors [1]. Nuclear space power rockets have obvious advantages by greatly reducing the mass of the propellant and potentially decreasing the cost. Nuclear thermal rockets use hydrogen propellant with the exhaust temperature more than 2500 K, which is very high, so an efficient and stable cooling technologies is required for the cooling of the nozzle surfaces. Supersonic film cooling, which is the employment of a secondary cooling fluid injected through holes or slots thus forming a cooling film to protect a surface exposed to a high-temperature environment, is a potential solution to this problem. Most of the previous studies [2-3] used the two dimensional straight channel with backward-facing step model. However, the nuclear rocket exhaust using the de Laval nozzle, which is a converging-diverging channel, especially in the diverging section, the Mach number increases rapidly, so it is different from the cases of two dimensional backward-facing step model which was mainly been used in most of previous studies. The present study numerically investigated the influence of coolant inlet height and Mach number on supersonic film cooling in the diverging section of de Laval nozzle, the results showed that both of increasing the coolant inlet Mach number and the coolant inlet height can obviously increase the film cooling effectiveness.

MODEL

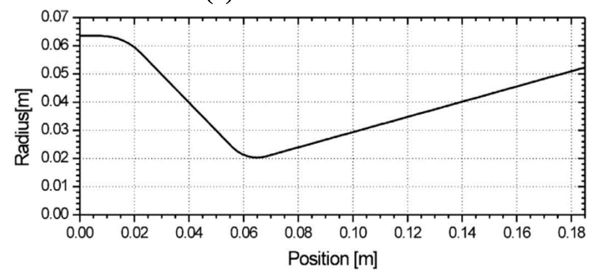
The de Laval nozzle for calculation used geometry from Back et al. [4]. The radius of the mainstream inlet is 63.5 cm, the nozzle-throat radius is 20 cm, the nozzle-inlet radius of curvature is 12.7 cm, the nozzle-throat radius of curvature is 20.32 cm, the conical nozzle investigated has 45° half-angles of convergence, 15° half-angles of divergence. And expansion-area ratios up to 6.6.

In the present study, the effect of coolant inlet height and coolant Mach number on supersonic film cooling were numerically investigated in the diverging section of the de Laval nozzle.

Supersonic film cooling was used in the nozzle diverging section, as is shown in Fig. 2. Two cases were studied with coolant injector heights of s = 0.5 mm, s = 1 mm, the thickness of the separating lip is t = 0.2 mm.



(a) Nozzle model



(b) nozzle profiles

Fig. 1 nozzle model and nozzle profiles.

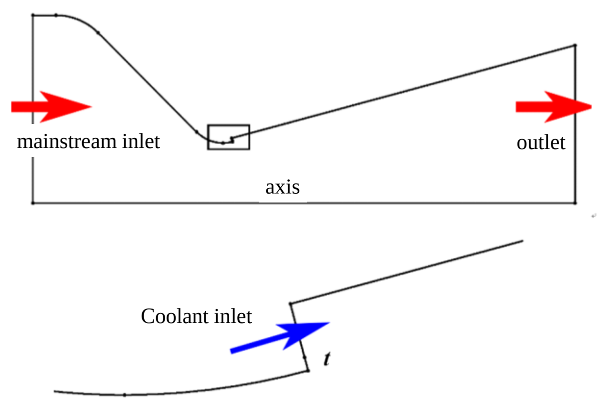


Fig. 2 Supersonic film cooling geometry.

A numerical simulation was conducted using the CFD code ANSYS FLUENT 14. The compressible Navier-Stokes equations for ideal gases were solved in this study. The shear-stress transport (SST) k-ω model was used for the turbulence closure.

The calculations used the density based solver with the implicit formulation. The central difference algorithm was used to evaluating the diffusion and pressure terms in the momentum equation and the divergence terms in the mass continuity equation. The advection terms in the momentum, energy, and turbulent kinetic energy were discretized using the second order upwind algorithm. The iterations were continued until the relative residuals were less than 10^{-3}.

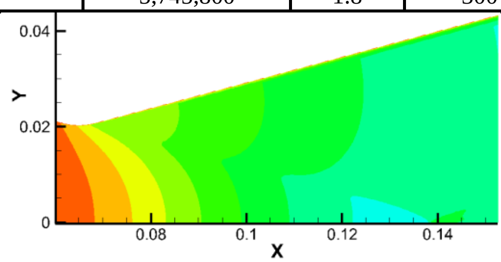
The mainstream temperature was 2500 K and the coolant stream temperature was 300 K. The mainstream total pressure is 6 MPa, and the static pressure of the mainstream and the injectant was well matched to avoid shock wave at the coolant inlet region, the total pressure of the coolant stream was changed to investigate the influence of Mach number, the detailed boundary condition is shown in Table I.

RESULTS

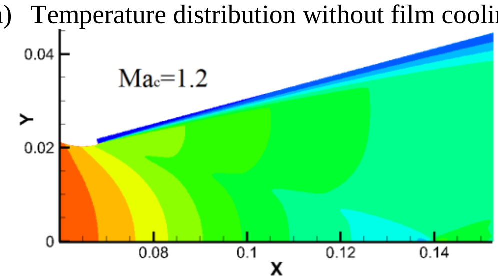
The static temperature distribution of the nozzle in the diverging region are shown in Fig. 3, the results showed that, without film cooling, the temperature of the surface is very high, with the 300 K coolant gas injects from the coolant injector and forms supersonic film cooling, the temperature near the wall decreases.

Table I Calculation condition

	Total pressure (Pa)	Mach number	Temperature (K)
Mainstream	6,000,000	-	2500
Coolant stream	2,425,000	1.2	300
	3,671,000	1.5	300
	5,745,800	1.8	300



(a) Temperature distribution without film cooling



(b) Temperature distribution with film cooling

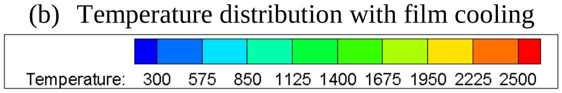
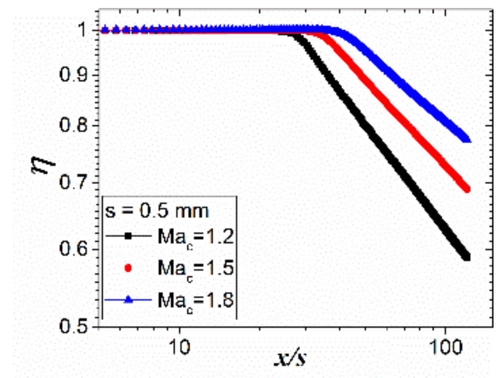


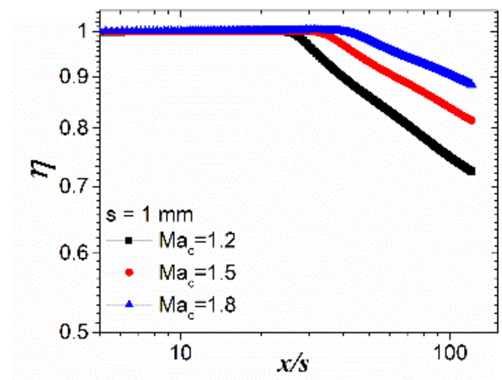
Fig. 3 Temperature distribution.

The film cooling effectiveness under different coolant Mach number are shown in Fig. 4. The results showed that, for the same coolant inlet height, as the coolant inlet Mach number increases, the film cooling effectiveness increases.

The film cooling effectiveness with different coolant inlet height are shown in Fig.5. The results showed that for the same coolant inlet Mach number, film cooling with higher coolant inlet height has obvious advantages.

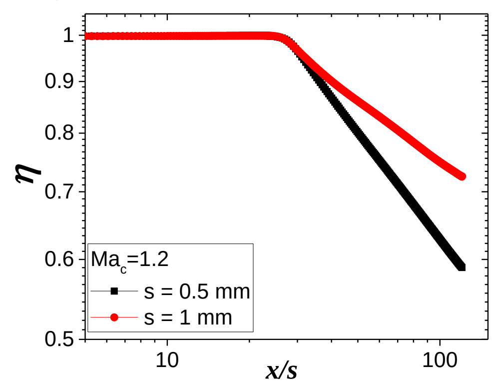


(a) *s*=0.5mm

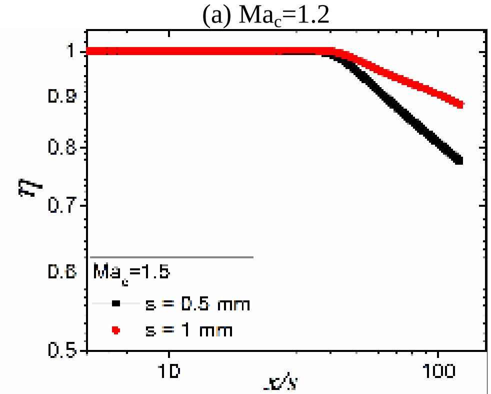


(b) *s*=1mm

Fig. 4 Influence of coolant Mach number .



(a) Ma_c=1.2



(b) Ma_c=1.5

Fig. 5 Influence of coolant inlet height.

CONCLUSIONS

The present study numerically investigated the influence of coolant inlet height and Mach number on supersonic film cooling in the diverging section of de Laval nozzle, with the results showing that: increasing the coolant inlet Mach number and the coolant inlet height can obviously increase the film cooling effectiveness.

ACKNOWLEDGEMENTS

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