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Control of High-Temperature Supersonic Impinging Jets Using Microjets

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The flowfield associated with supersonic impinging jets has been of interest to both engineers and researchers for some time due to its wide range of practical applications and its complex nature from a fundamental fluid dynamic point of view. An example of supersonic impinging jets occurs in short takeoff and vertical landing aircraft, for which the highly oscillatory flowfield and the associated acoustic loads are also accompanied by a dramatic loss in lift during hover, severe ground erosion of the landing surface, and hot gas ingestion into the engine inlets. Another characteristic feature of this flowfield is an intensive heat transfer between the jet and the impingement surface. In the past we have examined impinging jets and their control using microjets at cold conditions; the present study is a step toward examining this flowfield and the effectiveness of microjet control at increasingly realistic thermal conditions. An ideally expanded, Mach 1.5 primary jet issuing from an axisymmetric nozzle was heated up to a stagnation temperature of ∼500 K. Mean and unsteady temperature and pressure measurements were obtained on a lift plate representative of the undersurface of an aircraft and on the ground plane over a range of nozzle-to-plate distances (representing aircraft hover conditions). In addition, near-field noise was also measured using a microphone. The velocity field of the impinging jet for both cold and hot conditions was mapped using particle image velocimetry. Our results show that the temperature recovery factor at the stagnation point on the ground plane is strongly dependent on the temperature ratio and nozzle-to-plate distance, similar to observations in subsonic impinging jets. The hover lift loss for hot jets is much higher than for cold jets, nearly 75% of the primary jet thrust at small nozzle-to-plate distances. The pressure fluctuations generated by hot impinging jets are also substantially higher than their cold counterparts. As in cold jets, pressure and noise spectra for hot jets show discrete, high-amplitude acoustic tones (generally known as impinging tones) at frequencies varying with jet temperature. The activation of microjet control shows a substantial reduction in pressure fluctuations both in terms of overall sound pressure levels (up to 20 dB on the ground plane and 15 dB on the lift plate) and the attenuation of discrete, high-amplitude impinging tones (up to 32 dB). High-temperature peaks were observed in the temperature spectra at frequencies corresponding to impingement tones in the pressure and noise spectra; these were also substantially attenuated with microjet control. As much as 50% of the lift loss was recovered by using control for hot jets at smaller nozzle-to-plate distances. In general, the results provide evidence of the feasibility of using this active control approach under increasingly realistic conditions to achieve desired reductions in noise, unsteady pressures, and thermal loads.

I. Introduction

MANY examples of flow impingement of a jet on a solid surface can be found in engineering applications, including the launch of a rocket, takeoff and landing of a short takeoff and vertical landing (STOVL) aircraft, thrust vector control of a solid rocket motor or an aircraft exhaust, turbine blade cooling, electronic equipment cooling, and paper drying. For an efficient design of such systems, it is important to understand the flowfield associated with impinging jets. In particular, STOVL aircraft during hover produce high-temperature impinging jets on the landing surface. These lift-producing jets result in a high-temperature, turbulent, and highly oscillatory flowfield. This leads to severe ground erosion of the landing surface, lift loss due to entrainment of high-speed flow near the nozzle exit, very high unsteady loads on the nearby structures, and hot gas ingestion into the engine inlets. High levels of overall sound pressure levels (OASPL) associated with high-temperature supersonic impinging jets are a cause of concern due to sonic fatigue failure of the aircraft structure and a major source of noise pollution for personnel in the aircraft vicinity.

The flowfield properties of a supersonic impinging jet have been investigated by many researchers in the past, including Donaldson and Snedeker [1], Lamont and Hunt [2], Powell [3], Tam and Ahuja [4], Messersmith [5], Alvi and Iyer [6], Krothapalli et al. [7], and more recently Henderson et al. [8]. These studies clearly demonstrated the unsteady behavior of impinging jets and the presence of high-amplitude discrete impinging tones. Krothapalli et al. [7] demonstrated that generation of large-scale structures in the jet shear layer induces high entrainment velocity near the nozzle exit and, in turn, significant lift loss during hover. It is now well known that the highly unsteady behavior of the impinging jets is due to a feedback loop between the flow and acoustic fields, which leads to the aforementioned adverse effects. The concept of the feedback loop and its understanding has its roots in the pioneering research of Powell [9], who explained the feedback loop associated with edge tones generated by high-speed jets. A number of the general features of the feedback loop associated with impinging tones are similar to that elucidated by Powell for edge tones. (It should, however, be noted that despite the overall similarities in terms of flow-acoustic resonance, there are differences in many of the details. As an example, the sound producing source mechanisms, a subject of considerable research, in the two flows may be different). In a similar manner, as noted by Tam and Ahuja [4] and detailed by Krothapalli et al. [7], the feedback loop in the impinging jet is initiated as instability waves in the shear layer of the jet at the nozzle lip. These instability waves grow in size into large-scale vortical

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