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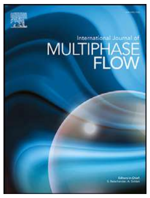

Experiments on water vapour condensation within supersonic nozzle flow generated by an impulse tunnel

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ABSTRACT

An impulse facility for analysis of water vapour nozzle flows using both shock tunnel and Ludwieg tube operating modes has been developed and tested at the University of Southern Queensland. Unique high-speed flow visualisation of the water vapour condensation shock has been acquired in the throat region of a nominally two-dimensional convergent-divergent nozzle with a 120 mm^2 throat area. This paper presents the facility performance and the time-resolved visualisation results for the nozzle flow, and the results are analysed with the aid of image post-processing tools and quasi-one-dimensional (Q1D) thermodynamic calculations. The experiments have produced qualitative and quantitative data on the flow conditions at four different relative humidity values from 25% to 100%, and over a range of nozzle supply temperatures between 293 K and 343 K. The direct measurement of the pressures and wave speeds within the tunnel resulted in a good agreement with the ideal gas Q1D calculations, particularly for the first incident shocks and expansion waves. Differences progressively increased with the number of reflections, due to the effect of viscous dissipation and the non-ideal end-wall interaction caused by the presence of the nozzle inlet. Moreover, flow visualizations of the location and orientation of both the weak disturbance waves and the condensation shock enabled the investigation of the supersonic water vapour condensation within the nozzle of this impulse facility. Based on these measurements, the nozzle flow downstream of the condensation shock was demonstrated to have a lower Mach number relative to the dry nitrogen flow case. This phenomenon is due to the phase change heat release, which appeared to be more significant when the condensation shock intensity was higher. Although further development of the apparatus is possible, the impulse test-rig configuration that we have developed permits a relatively high flow rate of test gas for a short period of time, leading to significantly reduced operating expenses relative to a continuous flow facility with the same mass flow rate. It is therefore suggested that future studies further improve and test the impulse facility techniques for studying condensation phenomena as a potential alternative to high-power, continuous flow facilities.

1. Introduction

Non-equilibrium condensation of steam occurs in many jet and turbomachinery devices, such as supersonic nozzles and across low pressure stages of steam turbines. Normal operation of these devices involves very high expansion rates that lead to a substantial departure from the equilibrium process Grazzini et al. (2018). As the steam accelerates inside a nozzle or blade vane, thermodynamic equilibrium is not maintained and, at a certain degree of expansion, the vapour state collapses and condensation takes place as a "condensation shock" Wegener and Mack (1958). This sudden phase change leads to a localized heat release that increases the pressure and temperature and reduces the Mach number Wegener and Mack (1958). Downstream of the condensation shock, the flow contains a considerable number of tiny liquid droplets (of the order of 10^{19}/cm^3, Hill (1966)) that can interact in non-trivial ways with shock waves and turbulent structures.

Experimental analysis of condensation shocks can be performed by at least two different techniques: the first involves condensation in cloud and expansion chambers and is commonly used in meteorological studies. The second deals with the analysis of supersonic expansions in De Laval nozzles. This last approach is generally employed in the fields of turbomachinery and aerodynamics

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