RESEARCH NOTE

Experimental results for nucleating steam flow in a two-dimensional supersonic duct and comparison with theory

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Results are presented of experiments conducted in a two-dimensional duct carrying a supersonic flow of condensing steam. The measurements comprised static pressure readings along the profiled surfaces of the duct and 'fog' droplet sizing using a light attenuation technique. Three sets of results for dry supercooled and nucleating steam flows are presented, and are compared with the predictions of a two-dimensional numerical calculation method

Keywords: *two-phase flow, air-lift pumps*

Over the past five decades, a considerable amount of data have been accumulated from tests of condensing steam flows in straight converging–diverging nozzles (see Refs 1 and 2 for reviews). Such tests are very suitable for verifying one-dimensional solutions of the equations of motion for wet steam because the condensation zone is well defined by a region of rising pressure colloquially known as a 'condensation shock'. Recent years, however, have seen the development of computational methods for non-equilibrium steam flows in two-dimensional geometries such as turbine cascades, but, as yet, few experimental measurements are available for comparison. In fact, the only relevant published data are by Bratos[3] and Kròl[4]. The experiments by Bratos used moist air as opposed to pure steam and those by Kròl were conducted in a straight converging–diverging nozzle with a high angle of divergence. This only produced a small two-dimensional effect, symmetrical with respect to the centre-line of the nozzle.

This research note describes an experimental investigation of nucleating steam flow in an asymmetric two-dimensional duct and includes a comparison with the theoretical predictions of a 'time-marching' calculation method.

Experimental apparatus

The two-dimensional duct was formed by two profiled blocks, each 240 mm long, sandwiched between two side plates as shown in Fig 1. The coordinates and dimensions of the duct are given in Table 1.

When operating with a low back pressure, an asymmetric supersonic flowfield was established downstream of the geometrical throat. For moderate degrees of superheat at the duct inlet, the steam expanded through the throat in a dry supercooled condition and reversion to equilibrium occurred in the supersonic region via the nucleation and rapid growth of a large number of very fine 'fog' droplets. The position of the condensation zone could be adjusted by altering the steam inlet conditions. The average expansion rate† through the duct was 1200/s, but this varies across the duct due to the asymmetry of the flowfield.

Static pressures along the convex and concave surfaces were measured using 24 pressure tappings 1 mm in diameter. Optical ports for 'fog' droplet size measurements were provided at two positions on the side plates near the convex and concave profiles respectively, some 110 mm downstream of the throat. This arrangement allowed measurements of the variation in droplet size across the duct to be made.

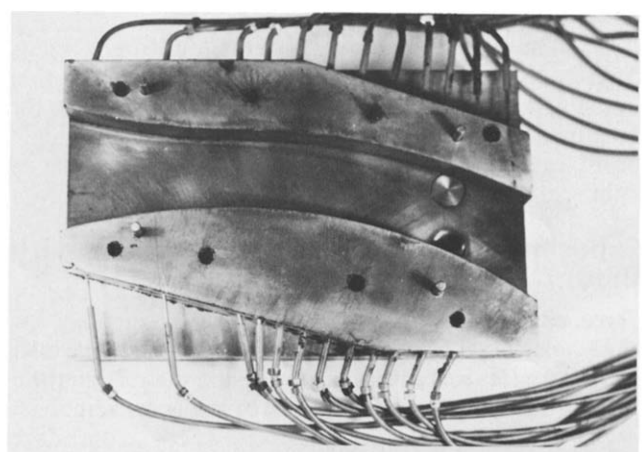

Fig 1 View of the experimental two-dimensional duct (scale 1:4)

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†The expansion rate is defined as $d(\ln p)/dt$, where p is the static pressure

Table 1 Dimensions of the experimental curved duct

X, mm	Convex surface Y, mm	Concave surface Y, mm
−87.00	268.17	331.83
−82.00	269.49	330.51
−70.20	272.30	327.70
−59.59	274.45	325.55
−51.63	275.83	324.17
−41.02	277.37	322.63
−30.41	278.56	321.45
−19.80	279.39	320.61
−11.84	279.78	320.22
−1.22	279.99	320.00
9.39	279.83	319.87
20.00	279.25	319.42
30.61	278.23	318.64
41.22	276.79	317.52
51.84	274.90	316.07
62.45	272.57	314.29
70.41	270.52	312.72
81.03	267.37	310.33
91.63	263.74	307.59
102.25	259.59	304.49
110.28	256.14	301.92
120.82	251.04	298.16
131.43	245.34	294.01
142.04	239.02	289.47
150.00	233.83	285.79

Duct depth = 22 mm
Optical window ports: Two ports at $X=110$ mm, each offset by 10 mm from the convex and concave surfaces
X is measured from the geometrical throat
Y is measured perpendicular to the X-direction

The instrumentation was as follows:

(1) An enclosed NiCr/NiAl thermocouple junction for measuring the steam inlet stagnation temperature.
(2) A silicon diaphragm pressure transducer for measuring the steam inlet stagnation pressure.
(3) A 24-port rotary switch valve connected to a transducer for measuring the static pressure distribution along the duct profiled surfaces.
(4) Light attenuation apparatus for 'fog' droplet size measurements.

The optical equipment used for 'fog' droplet sizing, described elsewhere[5], is similar to that used by other investigators[6,7]. The technique involved measuring the attenuation (due to scattering by the droplets) of a light beam traversing the flow. The theory of droplet sizing by light scattering is described by La Mer[8].

Experimental results and comparison with theory

Three sets of measurements taken at approximately the same inlet stagnation temperature, but different inlet pressures are presented below. The inlet stagnation pressures p_0 and temperatures T_0 of the tests were:

Test 1	$p_0=0.60$ bar	$T_0=388$ K;
Test 2	$p_0=0.81$ bar	$T_0=383$ K;
Test 3	$p_0=1.01$ bar	$T_0=383$ K.

In Test 1, the steam temperature was sufficiently high for the vapour to remain dry and supercooled throughout the working section. In Tests 2 and 3, however, nucleation and reversion to equilibrium occurred in the supersonic region of the flow. The recorded data, including the measured droplet sizes for the nucleating tests, are shown in Fig 2.

Superimposed on the experimental points in Fig 2 are the theoretical predictions of a calculation scheme for two-dimensional non-equilibrium wet steam flows. The method has recently been developed by the authors[10] and is an extension of the well-known Denton time-marching method for single-phase flow[9]. It uses a semi-analytical technique for treating the droplet growth and energy equations and consumes less computational time than other two-dimensional methods available for wet steam flows.

Fig 2(a) shows the pressure distribution along both the convex and concave surfaces for Test 1 where the steam remained dry and supercooled throughout the expansion. A moderate two-dimensional flowfield exists across the duct and the theoretical prediction is in close agreement with the measurements. The single scatter point in the middle of the duct is probably due to a fault in the static pressure tapping at that position.

Figs 2(b) and 2(c) show the results for Tests 2 and 3. It is evident from the graphs that there is significant variation in mean droplet radius across the duct despite the moderate two-dimensionality of the flowfield and the low expansion rate. The agreement between theory and

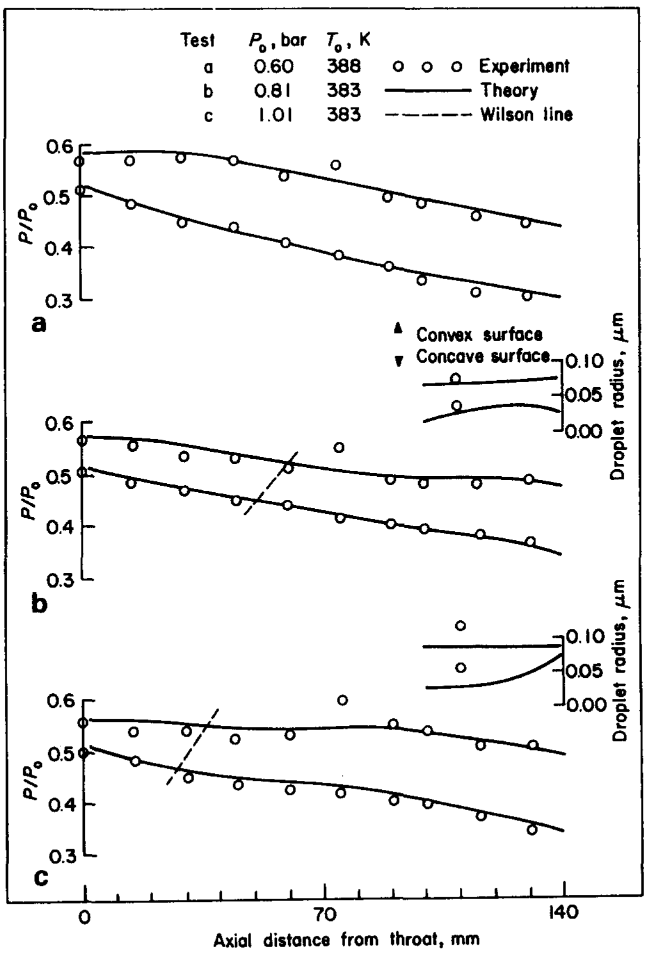

Fig 2 Comparison between the results of theory and experiment for the two-dimensional duct

experiment is consistent, however, and gives credence to the measurements.

The theoretical locations of the Wilson Points are indicated by the dashed lines on the figures. It is interesting to note that only slight pressure rises are created in the immediate downstream region. This indicates that, unlike near one-dimensional flows, two-dimensional flowfields tend to be capable of absorbing the heat release due to condensation without abrupt changes in the pressure and other flow variables.

Conclusions

By using a simple curved duct with low expansion rate, it has been possible to create a two-dimensional flowfield for wet steam and to obtain marked variations in pressure and mean droplet radius across the passage. Theoretical predictions using a numerical 'time-marching' technique show good agreement with the experimental results.

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