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Condensation phenomena in a turbine blade passage

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The mechanisms associated with the formation and growth of water droplets in the large low-pressure turbines used for electrical power generation are poorly understood and recent measurements have indicated that an unusually high loss is associated with the initial nucleation of these droplets. In order to gain an insight into the phenomena which arise in the turbine situation, some experiments were performed to investigate the behaviour of condensing steam flows in a blade passage. This study has revealed the fundamental significance of droplet nucleation in modifying the single-phase flow structure and results are presented which show the change in shock wave pattern when inlet superheat and outlet Mach number are varied. The trailing-edge shock wave structure appears considerably more robust towards variations of inlet superheat than purely one-dimensional considerations may suggest and the inadequacies of adopting a one-dimensional theory to analyse multi-dimensional condensing flows are demonstrated. Over a certain range of outlet Mach numbers an oscillating shock wave will establish in the throat region of the blade passage and this has been shown to interact strongly with droplet nucleation, resulting in a considerably increased mean droplet size. The possible implications of these results for turbine performance are also discussed.

1. Introduction

The design process by which blade profiles are produced for installation in turbines used for electrical power generation has reached a high degree of sophistication, combining advanced techniques of numerical and physical experimentation. However, consideration of one particular aspect of the flow in such machines has, to a large extent, been neglected and only recently has the potential importance of this oversight become apparent. In conventional or AGR plant the steam remains dry and superheated throughout the high- and intermediate-pressure turbine expansions and enters the low-pressure (LP) cylinders in this condition. At some stage within the LP turbine the steam cools to a saturated state, ultimately emerging with a wetness fraction of approximately 10%. In water-cooled nuclear plant, steam enters the high-pressure turbines saturated and will consequently remain in the two-phase regime for most of the subsequent expansion. The importance of this two-phase boundary lies in the fact that turbine-stages operating in the wet steam regime function at a lower efficiency than equivalent stages operating with dry steam. However, the mechanisms by which water droplets are first created in turbine expansions and the aerodynamic phenomena this process will induce, are the source of great uncertainty. Indeed, turbine manufacturers often consider wetness effects solely in terms of the now venerable Baumann correlation (which states that each percentage point wetness fraction present will give rise to an additional percentage point reduction in stage efficiency). This has little physical basis and obviously will inadequately represent the complex loss mechanisms which occur as a result of water droplets existing in the flow.

Various loss models have been assembled to account for wetness effects (e.g. Gyarmathy 1962; Moore 1976) and these indicate that considerably reduced output from the latter stages of LP turbines (and of course throughout the expansion in PWR plant) will potentially result from the presence of droplets in the flow. Until recent years, quantitative evidence from measurements made within operating turbines was absent; however, recent advances in instrumentation have been able to provide surprising information concerning the magnitude of this wetness loss. Walters (1985) describes some experiments in which the stage efficiencies of a turbine were measured at different levels of inlet reheat. Variation of this parameter alters the position at which water droplets are first nucleated and the results indicate that nucleation at a particular location is associated with an unusually high loss.

The ability to predict the occurrence of such an eventuality has obvious economic rewards; however, current knowledge is unable even to provide an explanation for the physical circumstances that may give rise to this loss. At present, a full understanding of the complex mechanisms associated with the onset of nucleation in a highly three-dimensional turbine flow appears a long-term objective. The most representative situation that can be easily investigated experimentally is condensation in a two-dimensional blade passage. This paper describes such an experiment and consequently seeks to establish the phenomena associated with condensation in this environment, thus providing important information regarding possible behaviour in the nucleating stage of a turbine.

2. Theoretical and experimental perspective

2.1. *Condensation in a one-dimensional nozzle*

Conventionally, the condensation process in a turbine is considered to be directly analogous to that observed in Laval nozzles operating at transonic speeds (figure 1). Steam enters in a dry superheated state and rapidly expands and cools as the flow accelerates. The rate of this expansion is too fast for the steam to remain in equilibrium and it cools below saturation conditions. The steam will then prevail in a metastable state of non-equilibrium (usually referred to as subcooled or supersaturated) until limiting extremes are reached at which random kinetic motions of molecules create sufficient stable microclusters for equilibrium to be resumed via condensation. This process is termed 'homogeneous nucleation' and despite numerous suggestions that alternative mechanisms for droplet creation are significant in the turbine situation (e.g. Deich 1984) there exists no evidence that homogeneous effects do not play an important, or indeed dominant, role. Many workers have been able to successfully predict the pressure distributions and droplet sizes measured in nozzle experiments (e.g. Moore *et al.* 1973; Bakhtar & Young 1976; Young 1982) by essentially combining variations of the so-called 'classical nucleation theory' (see, for example, Frenkl 1955) with growth laws similar to those employed by Gyarmathy (1962).

The release of latent heat into a one-dimensional accelerating flow, which occurs as a result of condensation from the vapour phase onto droplets, is known to give rise to a number of distinct flow regimes (Barschdorff 1970). The addition of this latent heat will cause the flow to tend towards unity Mach number although significant modification of the gasdynamic structure is only associated with the catastrophic

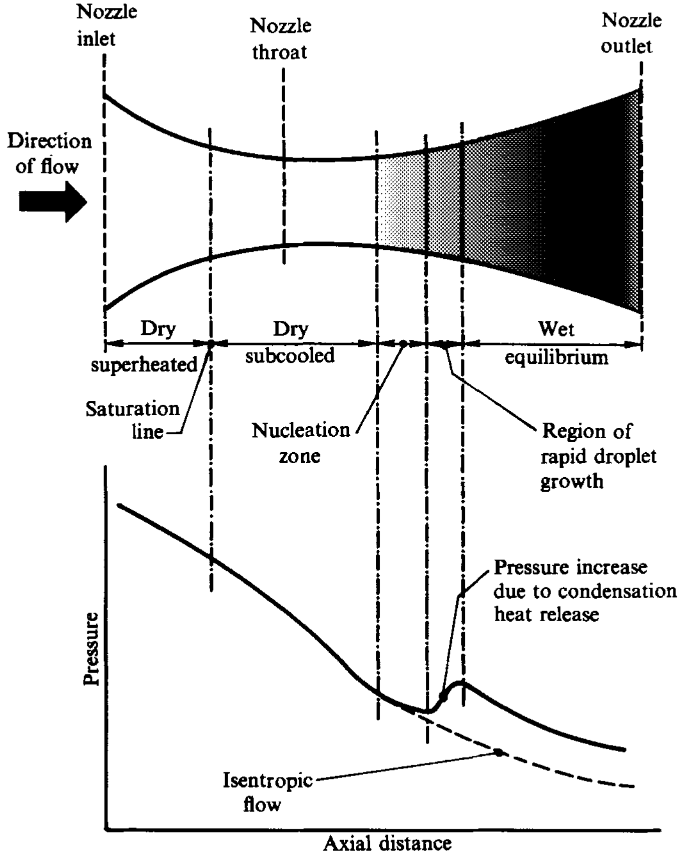

FIGURE 1. Condensation in a transonic Laval nozzle.

collapse of supersaturation arising after homogeneous nucleation. Assuming that acceleration commences from stagnation conditions which are approximately saturated or superheated, then the critical supersaturation is unlikely to be attained unless the flow is transonic. Consequently, heat addition to an initially supersonic flow is of particular interest and it is convenient to define a critical amount of heat, Q_{crit}, which is just sufficient to return the flow to sonic conditions. The relationship between condensation heat release Q and Q_{crit} will then categorize the flow into particular regimes (see Skillings & Jackson 1987).

The majority of experimental results reported in the literature for nucleating flows in nozzles have been produced for the case where $Q < Q_{\text{crit}}$. This regime is termed 'subcritical' and the flow remains steady, continuous and supersonic. However, attempts to predict nucleation in turbines using a simple one-dimensional model (Skillings, Walters & Jackson 1989) indicated that supercritical regimes ($Q \geqslant Q_{\text{crit}}$) were potentially common. In these cases, an aerodynamic shock wave will be established in the flow and this will either be steady or unsteady depending on the extent by which Q exceeds Q_{crit}. Recently, successful attempts at predicting such cases have been presented (Skillings, Walters & Moore 1987) where the Eulerian gas field equations are solved using MacCormack's explicit finite-difference scheme and the droplets are considered using a Lagrangian approach. From such a basis it is tempting to directly apply one-dimensional theories or extrapolate one-dimensional phenomena to the turbine situation. Of particular interest is the fact that the droplet size produced in cases of unsteady supercritical heat addition ($Q \gg Q_{crit}$) is considerably greater than in similar steady flows and since wetness loss is known to increase with droplet size, such a process within a machine would certainly enhance the loss. Several attempts at applying one-dimensional models to turbine flows have been presented in the literature (e.g. Bakhtar, Young & Ghoniem 1976; Bakhtar & Heaton 1981; Dibelius, *et al.* 1987). However, the following discussion will show that assertions regarding behaviour in a turbine based on highly simplified models should only be made tentatively and further information is required concerning condensation under more realistic conditions.

2.2. *Condensation in a blade passage*

As flow accelerates through a blade passage, it expands and cools in a similar fashion to the nozzle case. However, differential rates of expansion near the blade surfaces give rise to significant transverse gradients in flow parameters and the limiting supersaturation required to initiate spontaneous condensation will not be reached uniformly across the passage. The fastest expansion rate occurs near the suction surface and it is therefore expected that homogeneously nucleated water droplets will be generated at this position initially. The flow pattern encountered in single-phase transonic turbine blade cascades is described in standard texts (e.g. Gostelow 1984) and a schematic representation is given in figure 2. Experience gained with one-dimensional flows indicates that the appearance of a liquid phase in supersonic steam may or may not result in the formation of an aerodynamic shock wave and consequently it is unclear how phenomena associated with nucleation will interact with this single-phase flow structure. Experimental evidence from condensing steam cascades reported in the literature is scant and inconclusive and certainly insufficient to establish the changing shock structure as parameters such as inlet superheat or outlet Mach number are varied. Some examples of shock wave structures obtained in condensing cascades are shown schematically in figure 3. A distinct feature attributable to condensation is clear in all the examples although its position and orientation differ for each case and almost certainly depend on the particular blade geometry under investigation.

Furthermore, unsteady supercritical heat addition, which one-dimensional considerations have indicated to be potentially important, has, to the authors knowledge, only been observed in cascades where the throat lies well within the blade passage (Deich *et al.* 1987) and not in the more conventional situation where the throat is located near to, or coincides with, the blade trailing edge. However, Deich, Laukhin & Saltanov (1975) observed that flow in a blade passage was unstable with outlet Mach numbers in the range $0.9 < M_2 < 1.2$ for both dry superheated and condensing steam. They attributed this to a shock wave/boundary layer interaction and found that the presence of condensation in the passage tended to reduce oscillation frequency. This phenomenon has been studied in various blade geometries by other workers (e.g. Jaikrishnan 1979; Araki, Okamoto & Ohtomo 1980) and it appears that these oscillations occur when the trailing-edge shock impinges virtually normally onto the suction surface. It should be emphasized that these oscillations do not arise as a result of the inlet temperature being reduced and the condensation shock moving into an unsteady regime, but rather from an increase in back pressure moving the trailing-edge shock towards the throat. However, it is not inconceivable that nucleation in the throat region will interact strongly with the oscillating shock

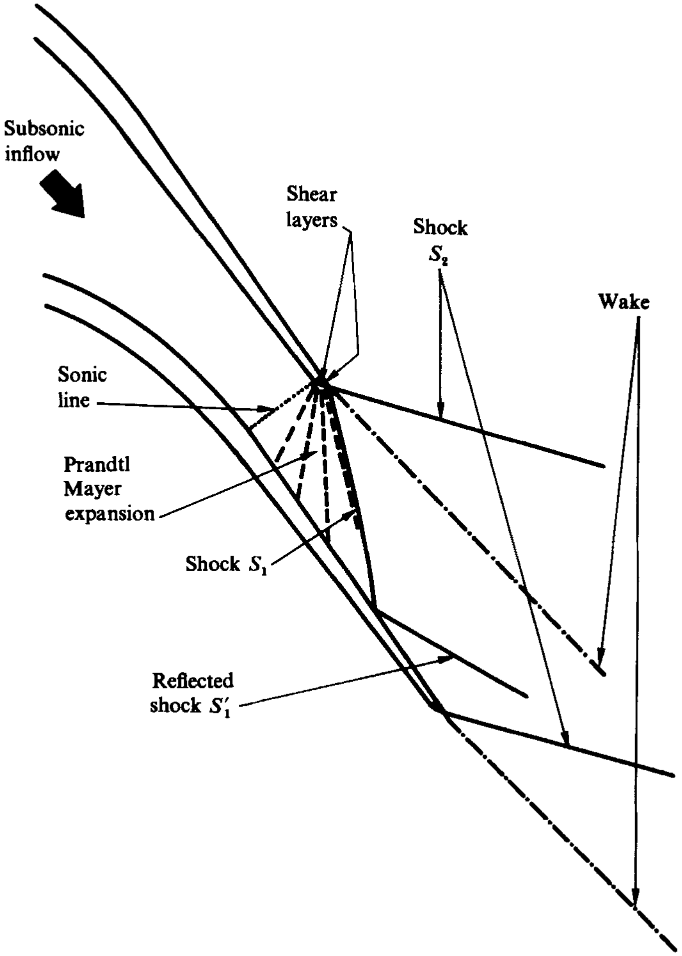

FIGURE 2. Transonic cascade flow structure.

in a similar manner to that occurring in the one-dimensional situation where condensation heat release is driving the oscillation.

From a theoretical viewpoint, numerical time-marching techniques used in concert with one of the high-speed computer processors now commonly available, present the opportunity that multi-dimensional condensing flows may be predicted. Such a program would have the potential to greatly enhance understanding of the condensation/aerodynamic interaction and, indeed, several codes have recently been developed which are capable of predicting nucleating flows in blade passages (Bakhtar & Mohammadi Tochai 1980; Simanovskii 1982; Moheban & Young 1984; Snoeck 1987). However, these techniques are in an early stage of development and inadequate experimental data has made rigorous validation problematic. Consequently, it is now opportune for experiments to be performed which provide more information concerning condensation in two-dimensional flows.

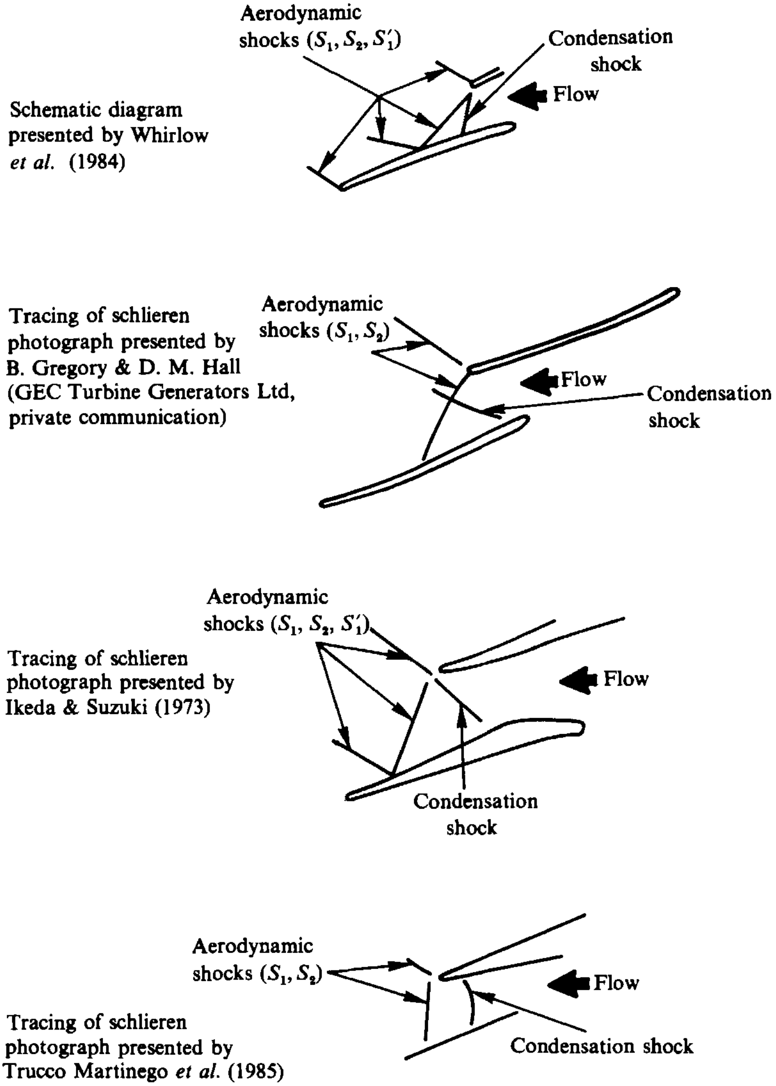

FIGURE 3. Examples of shock wave structures obtained in condensing steam cascades.

3. Cascade experiment

3.1. *Design considerations*

A series of experiments were undertaken to study various aspects of condensation in a cascade of turbine blades installed in the steam tunnel at the Central Electricity Research Laboratories (CERL) of the CEGB. The primary objective was not to produce a detailed quantitative analysis of the performance of the particular blade under investigation but rather to establish qualitatively the phenomena associated with condensation in a blade passage. This did not demand that flow periodicity was rigorously produced but simply that the flow accelerated to sonic conditions in a blade passage and exhausted into an environment where the flow was confined by steam emerging from similar passages on either side. This enabled the size of the blade sections to be maximized (thus facilitating easier blade instrumentation and

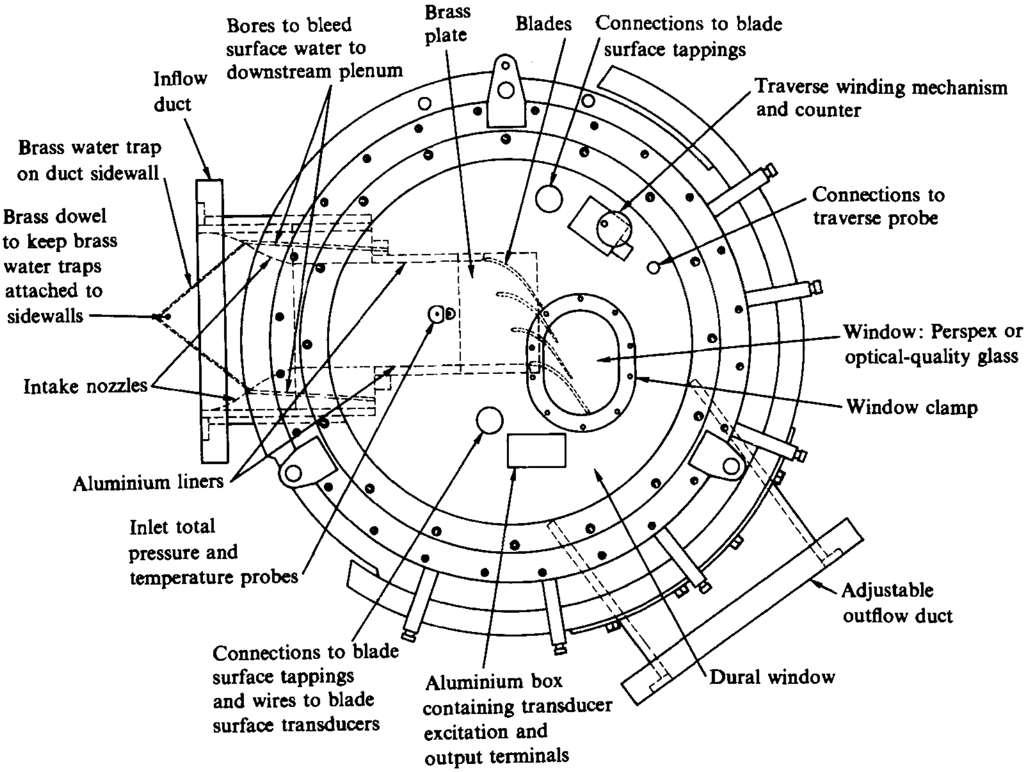

FIGURE 4. Test section.

providing a closer reproduction of actual flow conditions) given the limits imposed by the test facility (i.e. space and the ability to produce the correct transonic conditions). Four blades were manufactured using a profile typical of the stator blade in the nucleating stage of some LP turbines, and this consequently produced three passages. A schematic diagram of the test section is given in figure 4 and a detailed account of its design is presented by Skillings (1987).

3.2. *Instrumentation*

Cascade instrumentation was installed with the purpose of obtaining maximum information regarding flow behaviour in the central passage. Particular attention was paid to achieving clear flow visualizations of the trailing-edge shock wave structure. The schlieren technique was selected and ports to accommodate large optical-quality glass windows were constructed in the test section (these could be replaced by Perspex windows containing additional instrumentation when required). Attempts at schlieren photography of wet steam flows are often plagued by water rivulets running across the windows, resulting in considerable image deterioration. To overcome this problem, water traps were positioned upstream of the cascade and the water on the sidewall was bled to the downstream plenum, thus preventing contamination of the windows. A 35 mm camera was used to photograph shock systems that were essentially steady, whilst a high-speed Hycam camera (capable of taking up to 10000 frames per s) was introduced to analyse oscillating shocks. In addition to conventional blade surface pressure tappings, high-sensitivity piezoresistive pressure transducers were flush mounted on the blade to provide quantitative information concerning any fluctuating conditions that established in the flow. Measurements of the important droplet size parameter were obtained using the steam tunnel optical system which is described by Skillings *et al.* (1987) and which utilizes a technique developed by Walters (1973). No traverse of inlet conditions was attempted, relevant information being obtained from centrally mounted total pressure and temperature probes. A traverse mechanism was constructed downstream of the cascade to provide values for mean outlet Mach number, the total and static pressure probe employed being that described by Jackson & Walters (1979).

3.3. *Test conditions*

The CERL steam tunnel (described in detail by Moore *et al.* 1973) is capable of providing a wide variety of conditions within the test section. Inlet pressures can be generated which are typical of those encountered over the latter stages of LP turbines and this inflow can either be wet equilibrium or dry and with various levels of superheat. Also, selective closure of condenser passages will control the back pressure and consequently the outlet Mach number from the cascade. Exhaustive investigation into all possible permutations of test conditions was an intractable proposition and experiments were restricted to one regime of inlet pressure, i.e. $p_{01} \approx 0.36$ bars, which was approximately the value measured in the turbine situation for this blade section. It would have been desirable to increase the inlet superheat sufficiently to produce a completely dry flow and thus separate phenomena directly attributable to condensation. However, at this value of pressure, saturation temperature is ≈ 74 °C and consequently to ensure that condensation did not occur, an inlet temperature > 100 °C would have been required. Unfortunately, this is greater than the limiting inlet temperature the facility can produce. The inlet conditions were therefore restricted to wet equilibrium or dry with up to ≈ 15 °C superheat; however, all back pressures of interest were easily produced, thus providing a comprehensive range of supersonic and subsonic outlet flows.

4. Flow structure associated with nucleation in a blade passage

4.1. *Sensitivity towards inlet superheat*

In all flow visualizations, trailing-edge shocks S_1 and S_2 were clearly visible, often along with reflection S_1' from the blade back (see figure 2) and a reflection S_2' from the shear boundary. However, with a mean outlet Mach number $M_2 > 1.25$ an additional feature was observed just downstream from the throat which is inexplicable in terms of a single-phase expansion. This shock wave, which will be referred to as S_3, was strong and stable and can be attributed to condensation heat release.

Figure 5(*a*) shows a schlieren photograph of the shock wave structure with wet equilibrium inlet conditions and a mean outlet Mach number $M_2 \approx 1.41$. The steam tunnel produces wet equilibrium flows with a sauter mean droplet diameter $d_{32} > 1$ μm. Droplets of this size will be virtually inert towards interphase transfer processes and will certainly not prevent the supersaturation from developing until it reaches the critical level at which spontaneous condensation occurs. Therefore, flow phenomena will be very similar to those produced by a dry inflow. In most one-dimensional geometries, such an inflow condition would give rise to periodically unsteady shock waves (where $Q \gg Q_{\text{crit}}$). However, in a blade passage the transition to supersonic flow is associated with centred rarefaction waves at the trailing edge in which the expansion rates can be very high, and this will tend to oppose oscillations of this nature from establishing in the flow. Consequently, in a two-dimensional

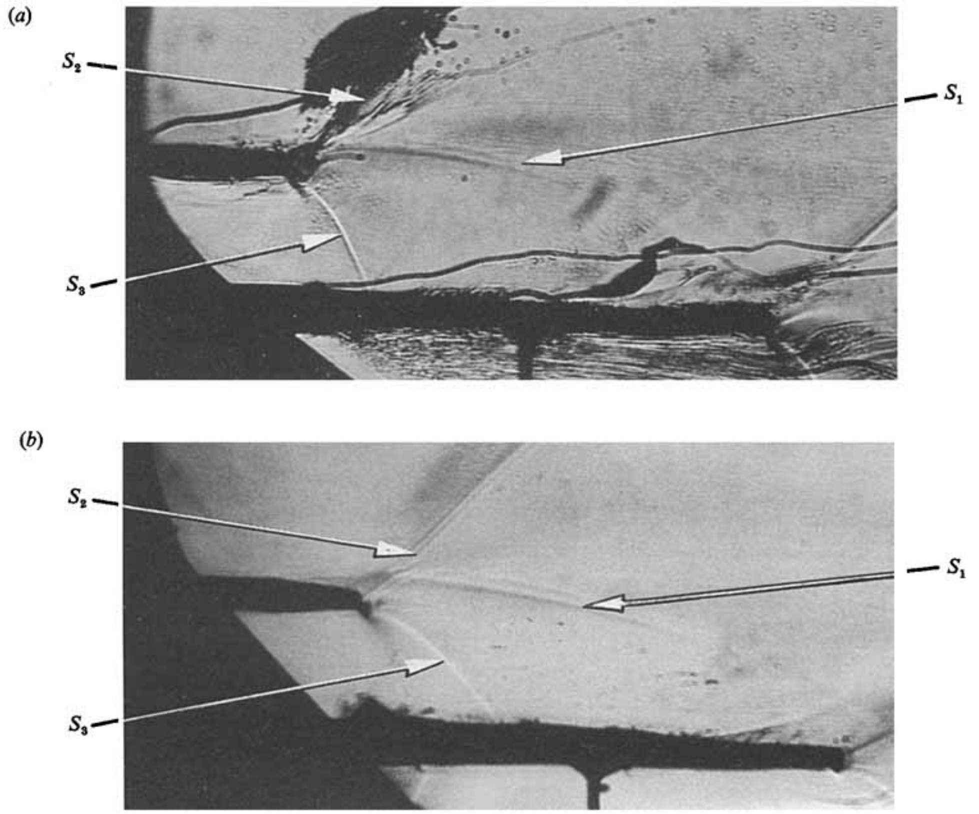

FIGURE 5. Schlieren photographs showing three trailing-edge shocks. (*a*) Wet equilibrium inflow; (*b*) dry superheated inflow ($\Delta T \approx 15$ °C).

passage a stable supercritical regime is produced where purely one-dimensional considerations may suggest an unstable flow to be more likely.

Figure 5(*b*) shows the flow structure for a mean outlet Mach number $M_2 \approx 1.49$ and an inlet superheat $\Delta T \approx 15$ °C. The shock pattern is very similar to that produced for a wet inflow, with the exception that the reflection point on the suction surface from condensation shock S_3 has moved significantly downstream. This can be explained in terms of the elevated inlet temperature delaying the onset of condensation and consequently the position at which heat is released into the flow. If this behaviour is again compared with that prevailing in a one-dimensional nozzle with similar inlet conditions, it would be expected that this level of superheat would delay the onset of condensation to the extent that a subcritical heat release ensued (i.e. $Q < Q_{\text{crit}}$). However, despite the shift in its position, S_3 is still evidently a shock wave and therefore a steady supercritical flow is produced in the blade passage where one-dimensional considerations may suggest that the flow would be subcritical.

These results would appear to imply that the shock structure is rather more robust towards the level of inlet superheat in a two-dimensional passage than in a one-dimensional nozzle. To explain these effects the influence of the differential blade surface expansion rates must be considered. The magnitude of the discrepancy between the extremes of the expansion rates within the passage and the expansion rate predicted using an equivalent one-dimensional geometry can easily be

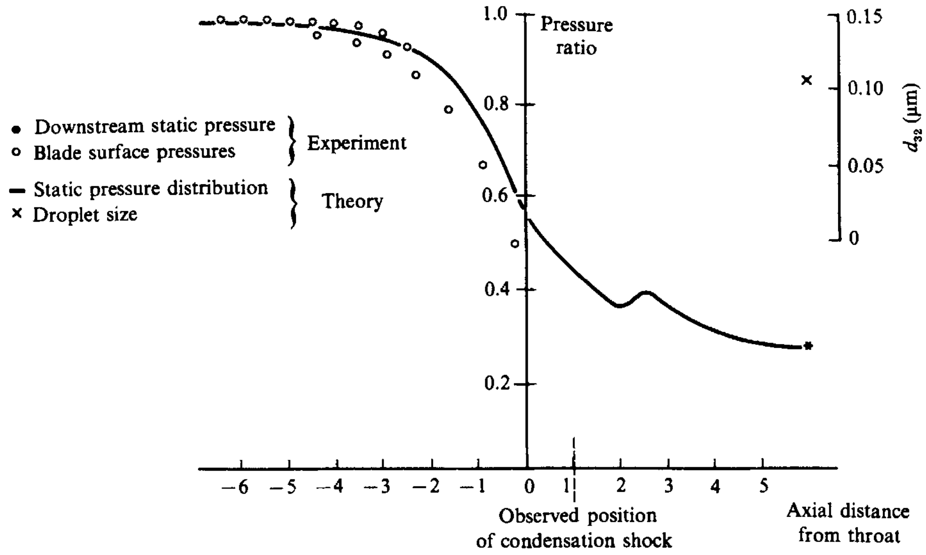

FIGURE 6. Comparison between one-dimensional theory and experimental results for inlet superheat $\Delta T \approx 15$ °C.

demonstrated. A procedure to transform a blade geometry into a one-dimensional equivalent is described by Skillings *et al.* (1989) and figure 6 shows the comparison between this one-dimensional theory and experimental results for the high-inlet-superheat case (the position of the blade surface pressure measurements having also been transformed to a one-dimensional equivalent). The one-dimensional theory employed is that described by Skillings & Jackson (1987) and it predicts an expansion rate which is much lower than that observed at the blade suction surface. Consequently spontaneous condensation was predicted to occur further along the passage than was observed experimentally and therefore falsely indicated that condensation heat release would be subcritical. It is also worth mentioning that for higher expansion rates over the nucleation zone more condensation centres are produced and these can only grow to a smaller size before equilibrium conditions are re-established. Therefore, it can be expected that the actual mean droplet size produced in this case was considerably smaller than the calculated value of ≈ 0.1 μm.

In a two-dimensional passage, it is evident that the critical supersaturation will be reached over a significant range of streamwise distance and the fact that heat release is much less localized in this situation explains how similar shock wave patterns may be produced for a wide range of inlet conditions. It would be of interest to investigate the pattern produced by higher inlet superheat or inlet subcooling although it appears that for this cascade geometry it is unlikely that the condensation shock could move sufficiently close to the throat for an entirely self-excited oscillation to be produced simply by altering the inlet temperature. It is therefore proposed that unstable supercritical heat addition will only be observed in blade passages were the throat is located well within the passage (see Deich *et al.* 1987) and not where the throat lies close to the blade trailing edge.

4.2. *Sensitivity towards outlet Mach number*

As the pressure ratio across the cascade was altered, the trailing-edge shock wave system underwent a sequence of changes which appeared reasonably independent of

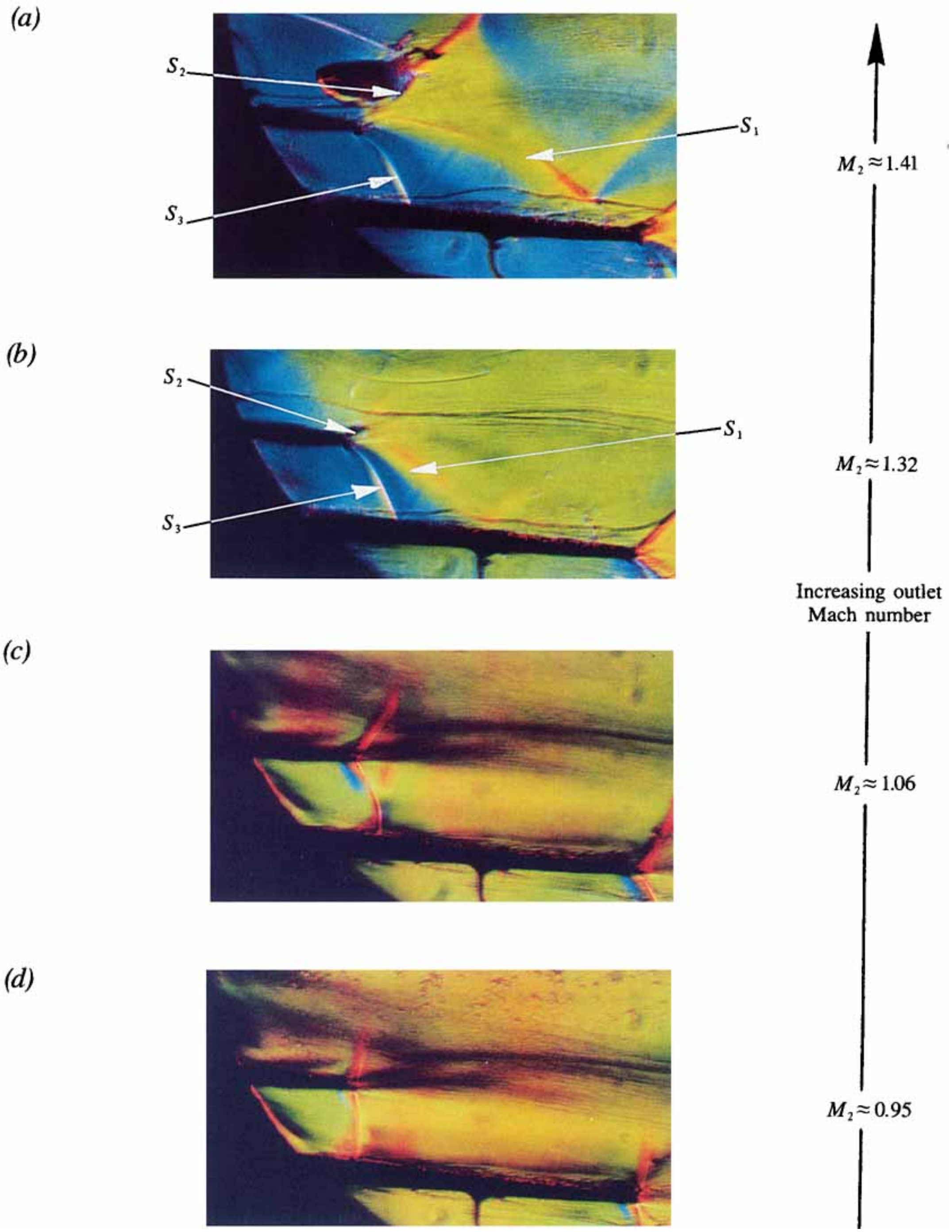

FIGURE 7. Change in trailing-edge shock structure as the outlet Mach number is altered (inlet superheat $\Delta T \approx 5\,^{\circ}\mathrm{C}$).

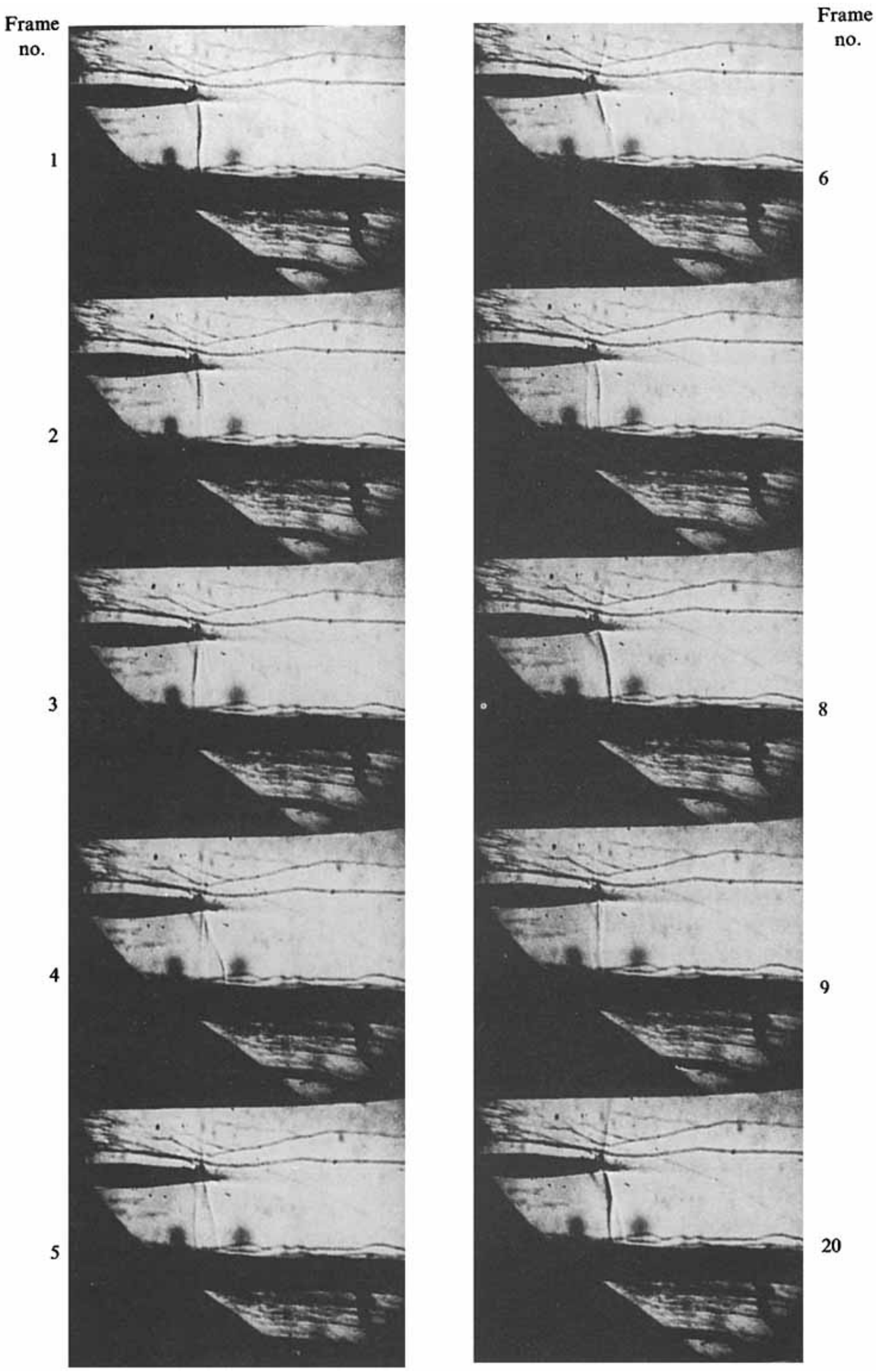

FIGURE 8. High-speed film of fluctuating throat shock for wet equilibrium inflow and $M_2 \approx 0.87$.

the level of inlet superheat. Schlieren photographs of the changing flow structure are given in figure 7 (plate 1) for an inflow which is dry and with low superheat (<5 °C). Figure 7(*a*) shows the situation with an outlet Mach number $M_2 \approx 1.41$. The shock pattern is very similar to those shown in figure 5 with S_1, S_2 and S_3 all present. Shocks S_1 and S_2 were both rather unsteady, which was probably largely a consequence of their interaction with the turbulent shear boundary although there is also evidence that the flow was separating near the reflection point of S_3 on the blade back. In contrast, the condensation shock S_3 was extremely steady and, indeed, it remained completely unaltered as the outlet Mach number was lowered to $M_2 \approx 1.32$ (figure 7*b*). Shocks S_1 and S_2 had both responded as expected to this change in back pressure although S_1 had weakened appreciably as it moved towards S_3. Before reaching S_3, S_1 disappeared and only then did the condensation shock begin to respond itself to the increase in pressure ratio and move towards the throat. With $M_2 \approx 1.06$ the conventional 'two shock' system was visible (figure 7*c*). Shock S_3 continued to become less oblique, maintaining stability until it lay almost directly across the flow passage (figure 7*d*).

Upon further increase in back pressure, shock S_3 began to execute strong periodic fluctuations, similar to those described by Deich *et al.* (1975). Figure 8 shows a series of consecutive exposures taken using the high-speed camera for wet equilibrium inflow and $M_2 \approx 0.87$. These photographs reveal the complex nature of this oscillation and, in particular, multiple shock images indicate that three-dimensional effects were potentially important. The appearance of this oscillation was recorded using piezoresistive transducers embedded in the blade just downstream of the throat (figure 9). Figure 9(*a*) shows a typical turbulent noise spectrum recorded over the range of outlet conditions $M_2 > 0.95$. For the outlet Mach number in the range $0.75 < M_2 < 0.95$ a series of discrete oscillations were observed with frequencies decreasing from $\nu \approx 3.2$ kHz to $\nu \approx 1.8$ kHz as the back pressure increased and with amplitudes up to ≈ 20 mbars (figure 9*b*, *c*, *d*). For $M_2 < 0.75$ the flow in the blade passage was completely subsonic and the turbulent noise spectrum returned (figure 9*e*).

It was shown by Skillings *et al.* (1987) that the presence of condensation induced shock oscillations in nucleating one-dimensional nozzle flows results in the creation of considerably larger droplets ($\approx \times 2$) than those produced in steady flows at similar conditions. This is due to a periodic 'quenching' of the nucleation zone as shock waves move towards the throat; fewer nucleation centres are then produced to relieve the supersaturation and they consequently grow to a larger size. The shock wave fluctuations observed in the throat region of the cascade would not have arisen as a result of the same forcing mechanism that produces those in the nozzle situation and at first sight it is unclear whether these oscillations interact with droplet nucleation. A test was performed which involved measurement of droplet size at similar conditions for steady and unsteady flows. Initially, an essentially steady flow was established with an inlet superheat ≈ 4 °C and a mean outlet Mach number $\approx$ unity. At this condition a mean droplet diameter of $d_{32} = 0.05$ µm was measured downstream of the cascade. With a similar inlet superheat, the measurement was repeated with the back pressure having been raised to produce an outlet Mach number ≈ 0.9 such that strong oscillations were observed near the throat (frequency ≈ 2750 Hz, amplitude ≈ 20 mbars). The droplet size measured for this oscillating case was $d_{32} = 0.11$ µm which was more than double that for the similar steady flow, a marked change in the extinction of any optical wavelength being readily observed.

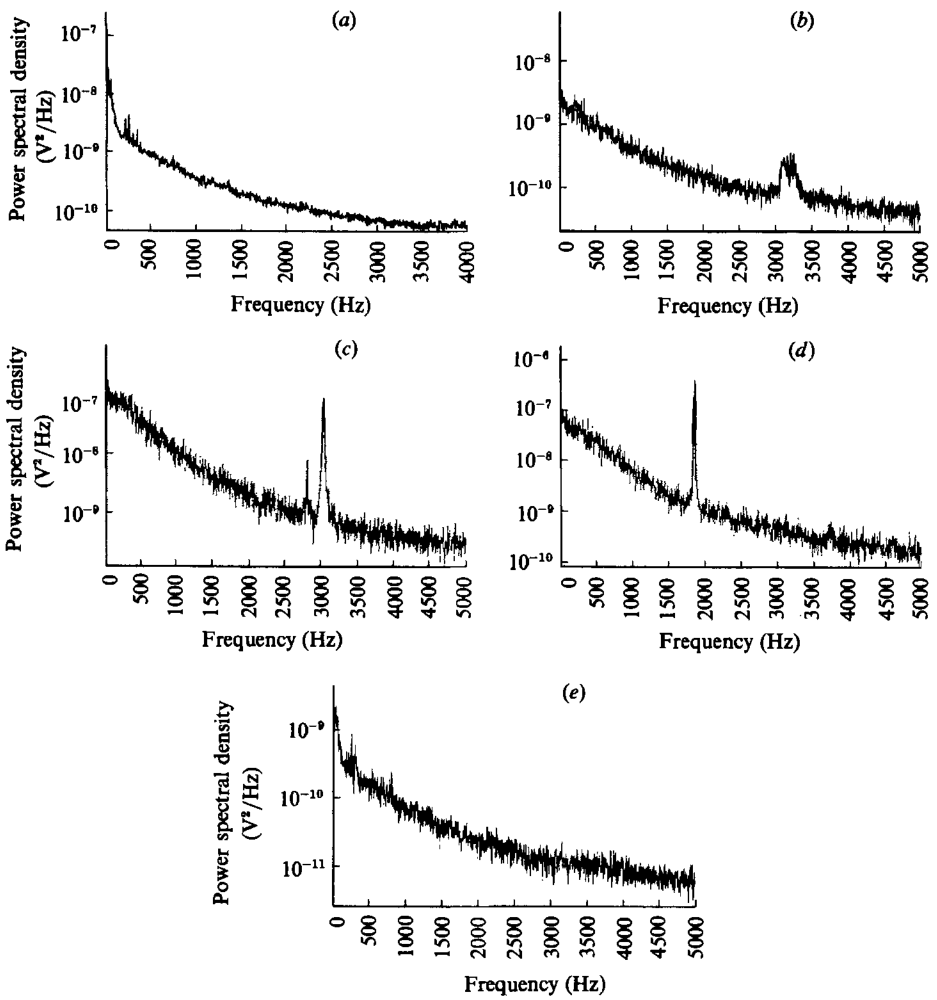

Figure 9. Appearance of throat oscillation as detected by blade-mounted pressure transducers. (*a*) $M_2 > 0.95$; (*b*–*d*) $0.75 < M_2 < 0.95$; (*e*) $M_2 < 0.75$.

It is, therefore, clear that the presence of a fluctuating shock wave in the nucleation zone of a blade passage will interact strongly with the condensation process and significantly affect the mean droplet size ultimately produced. To assess the importance of this effect for flow in a turbine it is again worth considering the non-localized nature of nucleation in a blade passage. Some droplet nucleation will arise in the throat region of the passage for a significant range of inlet conditions and, therefore, whenever the back pressure is such that instabilities arise, periodic quenching of the nucleation zone is likely to occur and the droplet size will be correspondingly larger. Since wetness loss mechanisms are known to depend upon droplet size, this effect will potentially reduce the efficiency of subsequent turbine stages. Also, it has been variously reported that a higher number of blade failures are associated with the nucleating stage in turbines (e.g. Povarov, Rabenko & Semenov 1984; Whirlow *et al.* 1984) and indeed, Whirlow *et al.* detected non-synchronous blade vibrations at this position within a machine. It is reasonable to speculate that the release of heat associated with the collapse of supersaturation will significantly alter the blade outlet Mach numbers from those calculated at the design stage using an equilibrium approach. Consequently, flows in nucleating blade passages are more likely to lie in the unsteady regime, thus placing greater demands on the structural integrity of the stage. It is possible that the instability of these weak shocks has been exacerbated by interaction with the turbulent shear boundary in the downstream plenum and this phenomenon might not extrapolate identically to the turbine situation. However, the need to include more rigorous non-equilibrium treatments in the turbine blade design process is evident.

5. Conclusions

Experiments have been performed on a cascade of turbine blades to study the phenomena associated with spontaneous condensation. A characteristic trailing-edge shock wave structure was found to arise and this pattern was fairly robust towards significant changes in inlet superheat. Indeed, subcritical and unstable supercritical regimes which occur in purely one-dimensional flows were not observed in the cascade over the range of inlet conditions investigated. In particular, it is concluded that condensation-induced shock oscillations are unlikely to establish in blade passages where the throat lies close to the trailing edge and especially in the actual turbine situation where levels of inlet supersaturation will probably be small. As the back pressure was raised, the three-shock system collapsed to a conventional two-shock system at a mean outlet Mach number of $M_2 \approx 1.25$. For mean outlet Mach numbers in the range $0.75 < M_2 < 0.95$, strong periodic shock wave fluctuations were observed in the throat region of the passage. Measurements of droplet size indicated that these oscillations were interacting strongly with the nucleation process and giving rise to considerably larger droplets.

These results have highlighted the inadequacies of employing a one-dimensional theory to analyse a highly two-dimensional flow of this type and greater understanding will only be forthcoming when techniques to predict condensation in two-dimensional passages are developed and refined. If wetness effects are completely neglected in the turbine design process then potentially important phenomena will not come to light. In particular, condensation heat release may be sufficient to move the condition into a regime of outlet Mach numbers where the flow is unsteady, thus potentially reducing turbine efficiency and reliability.

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