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WATER CONDENSATION IN LOW PRESSURE STEAM TURBINE: A NUCLEATION THEORY – PART II

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ABSTRACT

In the study of the condensation phenomenon in the operation of steam turbine, the existence of two-phase flow in the low pressure stage becomes significant in causing problems regarding the blade life span and efficiency reduction. The increase of wetness percentage in the steam turbine could reduce the overall efficiency of steam turbine. This second part of study highlights the extent of the evolution of the nucleation theory and its significant impact to the steam turbine blading design. Despite the central position of being power driven mechanism, only limited number of study have been carried out regarding the problems associated with the operation and design of these machines in comparison with that given to other prime movers. This paper will introduce some basic concept of the early to recent study towards investigating the nucleation theory in low pressure steam turbine.

Key Words : Steam turbine, Water condensation, Wetness, Prime movers

1.0 INTRODUCTION

Phenomena associated with condensation and phase change in flowing steam occurring in power cycles create numerous problems scientifically and technically which have been experienced over a century. As steam expands from an initially superheated state, it cools and at some point its temperature reaches the local saturation value and the fluid becomes saturated. With further expansion some of the vapour will eventually condense into liquid. Condensation on foreign nuclei, dust particles, ions etc. present within the vapour is termed *heterogeneous* nucleation. This is in contrast to *homogeneous* nucleation, where, in the absence of such surfaces, the path to condensation is by the fortuitous formation of liquid droplets within the vapour.

This paper will consider the theoretical background to the studies of two-phase flows of steam. The historical evolution of nucleation theory will be first presented. A typical example of condensing flow of steam in nozzles and related studies will be considered next. This will be followed by a discussion of condensation and problems associated with flows in turbines. The final part of the paper will concentrate on the investigations into two-phase two-dimensional flows of steam at the University of Birmingham and will provide a brief summary of the main steps of the progress made in the experimental aspects.

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2.0 METHODOLOGY

2.1 Theoretical Predictions

The first successful attempt to combine the nucleation theory and droplet growth equations with the gas dynamics equations was made by Oswatitsch [1]. His laborious hand calculations for the pressure distributions along the nozzle axis agreed with the experimental measurements using steam in convergent-divergent nozzles of Yellot [2] and Binnie and Woods [3] and the result of his own measurements using humid air.

Following Oswatitsch's success, other workers refined the theoretical treatment and used comparisons with measurements in convergent-divergent nozzles to validate the proposed refinements of the nucleation theory. The first theoretical study of nucleation in steam turbines is by Gyarmathy [4], who claimed the expansion rate $\left(-\frac{1}{P}\frac{dP}{dt}\right)$ to be the parameter controlling limiting supersaturation in the expansion of vapours. Investigations by Pouring [5], Puzyrewsky [6], Campbell and Bakhtar [7], and Filippov et. al [8] are examples of this line of work and have contributed significantly to the development of the subject.

There was a need for measuring the size of nucleated water droplets present within the wet steam. Such measurements were attempted in 1960's using optical techniques. Gyarmathy and Lesch [9], Petr [10], Walters [11] and Moses and Stein [12] were among the first to use this technique successfully. This data served as further basis for the validation of nucleation and droplet growth theories.

Studies of condensation process in high pressure steam relevant to wetness problems in PWR nuclear power plant have been carried out by Ryley and Tubman [13], Bakhtar et. al [14] and Zidi [15].

2.2 One-Dimensional Theoretical Treatment of Condensing Flows

Campbell and Bakhtar [16] originally developed the one-dimensional theoretical treatment available at the University of Birmingham which has been refined by others over the years, but the principle of the treatment has remained the same. In the light of its importance in validating the nucleation and droplet growth theories as well as its application to other problems to be reviewed this section will briefly discuss the treatment.

Condensing flow of steam can be regarded as a special case of the flow of a compressible fluid with heat addition, where the source of heat is the latent energy associated with the phase change. For the purposes of analysis, steam is taken as the summation of the liquid droplets of specified sizes uniformly distributed in the vapour which fills the space between them.

In this particular treatment, the droplet formation and growth equations are combined with the one-dimensional gas dynamic equations in differential form. Assuming no inter-phase slip, the volume occupied by the liquid to be small and that the vapour phase behaves as a perfect gas, the fundamental equations of motion for the steady one-dimensional flow of a condensing vapour over an incremental distance dx along the duct axis can be written as : -

Continuity :- $$m = m_G + m_L = constant \qquad (1)$$

$$\frac{d\rho_G}{\rho_G}+\frac{dA}{A}+\frac{dV}{V}+\frac{dm_L}{m-m_L}=0 \tag{2}$$

Momentum :-

$$\frac{dP}{P}+\frac{\rho_G V^2}{P}\frac{fdx}{2d_e}+\frac{\rho_G V^2}{(1-w)P}\frac{dV}{V}=0 \tag{3}$$

Energy :-

$$\frac{V^2}{C_p T_G}\frac{dV}{V}+\frac{dT_G}{T_G}+\frac{d(Lm_L)}{C_p T_G m}=0 \tag{4}$$

Equation of state :-

$$\frac{dP}{P}-\frac{d\rho_G}{\rho_G}-\frac{dT_G}{T_G}=0 \tag{5}$$

where m is the mass flow rate, V the velocity, d_e the equivalent diameter of the duct, w the wetness fraction, L the latent heat of evaporation and subscripts L and G refer to the liquid and vapour phases respectively. The friction factor, f is introduced to allow for fluid friction.

Condensation is by nucleation of new droplets and the growth of any droplets existing within the incremental step and the change of liquid mass, dm_L, can be determined by using the nucleation and droplet growth equations. The equation for nucleation rate derived from classical theory is reviewed together with the refinements due to Kantrowitz [17] and Courtney [18]. The growth of drops in the flow is determined by solving the equations describing the mass and heat transfer processes involved.

As the mass rate of formation of the liquid over the increment can be calculated, $fdx/(2d_e)$, dA/A and dm_L can be regarded as independent variables and Equations (4) to (7) solved for four unknowns dV/V, dT_G/T_G, dP/P and $d\rho_G/\rho_G$. The standard fourth-order Runge-Kutta technique is then employed to integrate the resulting expressions. Beginning with superheated steam at the inlet, the state path of the fluid is followed step by step through supercooling, nucleation and rapid condensation until the fluid returns to thermodynamic equilibrium and then its subsequent behaviour as wet vapour.

Using the treatment the sensitivity of solutions to values of condensation coefficient, friction factor and surface tension was investigated by Campbell and Bakhtar [7]. Although friction factor could be measured and was well reported in the literature, there was, at the time, some debate over the models adopted for the other parameters. In making comparisons with axial pressure measurements of Binnie and Woods [3], they were able to report good agreement. This was achieved either by adopting Benson and Shuttleworth's [19] model for the variations of surface tension and a value much smaller than unity for the condensation coefficient or by taking the surface tension of small clusters to be the same as that for bulk water and a condensation coefficient of unity.

In order to improve agreement with experimental results over a wide range of conditions, in later studies, the one-dimensional treatment was duly refined. The original treatment was for relatively low pressure and treated the vapour as a perfect gas. Young [20] and Bakhtar, Ryley, Tubman and Young [14] included the second virial coefficient in the equation of state to extend the range of the theoretical treatment. They obtained only moderate agreement with the first set of experimental results of condensation at high pressure but they attributed this, in part, to leakage past the sliding nozzle profiles used in the experimental study.

Piran [21] and Bakhtar and Piran [22] studied further the equation of state for steam and suggested that the virial equation of state due to Vukalovich [23] employing five virial coefficients was the most suitable for extrapolation into the metastable state. In addition Zidi [24] and Bakhtar and Zidi [25][26] developed a new semi-empirical self-diffusion coefficient for steam and using the Vukalovich equation of state were able to obtain good agreement with experimental measurements over a wide range of pressures.

The one-dimensional treatment has also been used to study other problems associated with two-phase flows, of which, choking and instability due to super-critical heat addition, are two important examples which will be briefly discussed in the following sections.

3.0 CHOKING CONDITION

In order to accelerate a single phase fluid (e.g. superheated steam) adiabatically from subsonic to supersonic conditions, the position at which sonic velocity is attained must coincide with the position of minimum area. In the case of a converging-diverging nozzle this position is the throat. The nozzle is said to be choked when a Mach number of unity is reached and the mass flow rate cannot be increased without altering the inlet conditions. The choking velocity is indeed the speed with which small amplitude disturbances propagate in the fluid.

The speed of sound in a two-phase mixture has been studied by Karplus [27] and Baum and Horn [28] amongst others. Konorski [29] and Petr [30] have shown that the speed of sound in wet steam varies between the equilibrium and the frozen speeds depending on the wave frequency. At high frequencies the waves travel with the frozen speed of sound defined as;

$$a_f = \sqrt{\gamma_f RT} \tag{6}$$

where γ_f is the isentropic exponent of the vapour phase alone. a_f represents the limit when the disturbances can propagate through the vapour phase without affecting the liquid. In contrast, the equilibrium speed of sound represents the case where the disturbances are of sufficiently low frequency, to allow the fluid to remain in thermodynamic equilibrium. This is defined as;

$$a_e = \sqrt{\gamma_e RT} \tag{7}$$

where γ_e is the isentropic exponent of the mixture under equilibrium conditions. Between these extremes, the propagation of disturbances will be associated with some exchange of heat, mass and momentum between the droplets and the vapour.

Bakhtar and Young [31] considered the parallel case of choking of a two-phase fluid flowing in a convergent-divergent nozzle and showed that the choking velocity at the throat is variable between the equilibrium and frozen speeds of sound depending on the conditions.

According to gas dynamic theory e.g. Shapirro [32], addition of heat to a perfect gas flowing in a frictionless constant area duct will cause a rise in temperature except when the Mach number is in the range $1/\sqrt{\gamma} < Ma < 1$, where it causes the temperature to drop while accelerating the flow. In the case of steam the determining parameter is supercooling. The analysis by Bakhtar and Young [31] shows that the effect of heat addition due to condensation on a wet steam flow in a frictionless constant area duct is to reduce the degree of supercooling, except in the Mach number range $Ma^+ < Ma < 1$, (Ma^+ is the critical Mach number which will be defined later), where the supercooling is increased while the flow is accelerated. Thus if at the entrance to the duct, the fluid has attained a Mach number greater than Ma^+ and is in a state of supercooling however small, the release of latent heat associated with any phase change will accelerate it to the sonic velocity providing the duct is sufficiently long. For low pressure steam Ma^+ is shown to be approximately 0.9. The choking criteria can be defined either by Ma^+ or attaining a Mach number of unity.

In a convergent-divergent nozzle, the rate of expansion after the throat corresponds with the frequency of the wave. The limiting case of the propagation of low frequency waves corresponds to choking in a nozzle in which the angle of divergence is zero. Thus, the critical Mach number at the throat is Ma^+ and the speed is equivalent to the equilibrium speed of sound. As the angle of divergence is increased, the critical Mach number at the throat will increase above Ma^+ until the Mach number reaches a maximum value of unity. Higher angles of divergence will have no effect on the flow properties and the flow will choke at the frozen speed of sound.

4.0 INSTABILITY DUE TO SUPER-CRITICAL HEAT ADDITION

It can be easily shown that the addition of heat to a supersonic flow will cause it to retard while the converse is true for a subsonic stream. In the case of a supersonic stream a limiting condition exists when the flow Mach number is reduced to unity. In this case, the flow would not be able to sustain any further heat release which will then result in a reduction in the mass flow rate.

This mechanism gives rise to unsteady effects in condensing flows and can be simply illustrated by considering a rapid expansion of superheated or saturated vapour in a convergent-divergent nozzle. Condensation normally occurs in the divergent section a short distance downstream of the throat with the consequence of considerable release of latent heat, Q, to the flow. The effect of this on the overall behaviour of the flow depends on the local Mach number, where the heat has been released and the amount of heat released by condensation.

The quantity of heat, Q_1, necessary to bring a supersonic flow just to sonic condition is a function of the Mach number alone. If the heat released by condensation, Q is less than Q_1, the flow remains continuous and stable, with the characteristic knee shape in the pressure distribution. If the heat added is more than Q_1, the upstream condition will be affected and the mass flow rate will be reduced. This will lower the throat Mach number below unity and cause the divergent section to act as a diffuser. With the downstream pressure maintained, the mass flow rises again and pulsation develops.

It is also possible to bring the flow to a Mach number of unity by first passing it through a normal shock wave making it subsonic and adding heat to accelerate the flow to the sonic condition. Denoting the heat necessary for this purpose by Q_2, it can be shown that for a perfect gas flowing in a frictionless constant area duct, $Q_1 = Q_2$. In practice the influence of friction and secondary effects cause Q_2 to exceed Q_1. Thus, depending on the duct geometry and fluid inlet conditions, in the case of nucleating flows three separate conditions are possible : -

1) $Q < Q_1 < Q_2$, the flow is stable and continuous. The released of heat by condensation causes a pressure rise in the flow field and the Mach number remains larger than unity throughout.

2) $Q_1 < Q < Q_2$, a normal aerodynamic shock develops within the flow and the pressure in part of the condensation zone exceeds the throat pressure, but the flow remains stable.

3) $Q_1 < Q_2 < Q$, pulsating flow develops. The addition of heat reduces the Mach number at the throat of the nozzle below unity, causing the diverging section to act as a diffuser. With the downstream pressure still maintained, the pressure drop across the

nozzle restores the sonic flow at the throat and condensation in the diverging section. The process then repeats itself giving rise to oscillations.

Schmidt [33] was among the first to discover *super-critical instability* in condensing flows when he observed that under certain flow conditions, the expansion of moist air in a nozzle led to oscillations. Subsequently, other investigators have studied the phenomenon experimentally and theoretically e.g. Gyarmathy [4], Pouring [3] and Barschdorff [34]. Barschdorff [34] performed an experimental investigation of the condensing flow of steam in a de Laval nozzle and successfully demonstrated the existence of the unstable conditions. Barschdorff [34] provided the theoretical explanation for such unsteadiness and gave some approximate relationship for the frequency of the periodic flow. Wegener and Mosnier [35] identified a frequency range of 300Hz-2kHz for the oscillations. This wide range of frequency is directly relevant to steam flows in turbines which encompasses typical blade passing frequencies. Yousif, Campbell and Bakhtar [36] considered the steam conditions at the end of the rapid condensation zone, where to be stable, Mach number must be unity as the limiting case and traced backwards to find the initial condition of steam at the nozzle inlet. They then plotted this locus of instability limit on a Mollier chart. Sichel [37] has formulated a similarity solution for flow in convergent-divergent nozzles and computed the response of the flow to various forms of unsteady heat input.

Skilling et. al [38] recently developed one-dimensional unsteady time-marching treatments for condensing flow of steam and demonstrated the phenomena numerically. The former used MacCormack's whereas the latter used Denton's method.

5.0 CONDENSATION AND WETNESS PROBLEMS IN TURBINES

The effect of the presence of the liquid phase on the efficiency of steam turbines has been recognised since the early 1900's. Baumann [39] from his observations proposed that every percentage wetness present in the stream caused a two percent increase in steam consumption. In 1921, he revised this theory with his famous one percent for one percent rule, in which he suggested that the efficiency of a turbine stage decreases by one percent for each percent of water present. Despite the very drastic developments in the operating conditions of steam turbines this rule which bears his name is still widely employed by turbine designers to date.

A tangible consequence of the presence of liquid in steam is erosion of blade surfaces, and was first observed in the 1920's. The problem was first investigated by Honnerger [40]. He recognised that erosion was caused mainly by droplets impacting on the blades and carried out simulated tests on different materials with water jets. His work was followed by von Freuderich [41], who developed a mechanical theory for erosion. Tests using rotating rigs were carried out by Honneger [40] and Gardner [42]. They showed that erosion could be reduced by hardening the affected surfaces. Drainage devices were also used, but were not as effective as had been hoped.

In the 1930's experience of wetness problems must have been widespread as a consequence of the gradual increase in the demand for and production of power. In the absence of superheaters, it was initially expected that increases in the thermodynamic efficiencies of the power cycles could be achieved by raising the inlet pressure. Unfortunately, this was also accompanied by increases in the steam wetness levels in the low pressure stages of the turbines. The erosion damage and losses caused by the increased wetness more than offset any increases in the efficiencies obtained by employing high pressures. Consequently, an arbitrary limit of 15 % was imposed on the wetness fraction at outlet from turbines.

With the introduction of reheat cycles there was temporary relief in these problems. The continual increase in demand for power led to the development of progressively larger steam turbine units. The corresponding increases in blade speeds led to considerable impact velocities, which brought renewed interest in wetness problems.

The consequences of the presence of wetness in steam turbines can be divided into three separate categories namely: mechanical, thermodynamic and aerodynamic.

The mechanical losses stem from the deposition of droplets on the stator and rotor blades as well as the drag of the droplets. The droplets nucleated within the steam deposit on the stator blades by the combination of direct inertial impaction and turbulent diffusion through the boundary-layers. They then form into films and rivulets and are driven to the trailing edges of blades by the drag of the steam. They are then re-entrained into the flow in the form of large droplets having a low absolute velocity. These droplets impinge on the next rotor blades with large relative velocities and high negative incidence exerting a braking effect and eroding the leading edges. In depositing on blade surfaces fog droplets give up their kinetic energy and the potential for doing work. Water deposited on the rotor blades is subject to strong centrifugal forces and moves towards the tip of the blades, where it is flung off in a radial direction. These droplets can be caught in conveniently placed belts and have no further effect on turbine performance.

The thermodynamic losses form the dominant part of the total loss. These results from irreversible heat transfer across finite temperature differences. The latent heat, released during condensation is given up to the liquid and is then transferred back to the parent vapour across a finite temperature difference and causes a rise in entropy.

The third aspect of the losses is the aerodynamic repercussions of the release of latent heat into the flow. The effect of the pressure rise due to condensation, supercritical instability and choking of the flow are examples.

Gyarmathy [4] made the first theoretical study of two-phase flow in steam turbines, introducing a new perspectives into the investigation of these problems. He applied his own simplified one-dimensional two-phase flow analysis originally developed for the prediction of Wilson points in de Laval nozzles to two hypothetical steam turbines, but his approach suffered from many weaknesses.

Many investigations into wetness problems in turbines have followed this work. Interest was initially concentrated on erosion problems in the sixties and seventies and a wealth of results covering many aspects of problem were reported, e.g. Gardner [42] and Stastny [43]. However, the more fundamental issue is the source of the liquid droplets causing the erosion damage, that is the deposition of finer droplets which in turn depends on the size of droplets formed during spontaneous condensation.

Using scale models of real turbines, Smith [44] reported substantial measurements of pressure, mass flow rate and overall efficiency of turbine stages under superheated and two-phase flow conditions.

Driven by the successful application of a one-dimensional theory to the flow in nozzles, Bakhtar and co-workers embarked on a number of studies applying this theoretical approach to the flow in steam turbines. One-dimensional equivalents were drawn up to represent the turbine passages and the aerodynamic losses were accounted for by friction factors. These studies include those of Bakhtar, Ghoneim and Young [45] and Bakhtar and Heaton [46]. The analysis was based on specific measurements in model turbines including the measured data of Smith [44]. One conclusion of their studies was that the thermodynamic component formed a significant part of the total loss. Their studies could be considered as an important step into further development of the theoretical treatment and provided substantial insights into features of condensing flows in turbines. Investigations into the condensation process in turbine flows were also reported by Gyarmathy [4] and Filippov et. al [47].

The size of fog droplets in operational turbines could be obtained using the most popular method of light scattering. *Walters* [10] has contributed significantly towards developing this technique but there is still considerable uncertainty about the size and distribution of droplets in turbines. The quantity of moisture present in the form of coarse water is more easily measured, especially in turbines with suction slots for its removal and is usually taken as a measure of deposition rates.

It is generally assumed that the observed coarse water stems from the re-entrainment of the deposited droplets. But the deposition rates based on the predicted sizes of the nucleated droplets are too small to correspond with the observed coarse water.

A general assumption about the condensation phenomena within turbines is that spontaneous condensation is the dominant aspect and heterogeneous condensation is neglected. However, there have been reports in the literature of cases where wetness was observed well in advance of the *Wilson* line. This provides an argument that homogeneous nucleation is not the sole means of droplet formation within a real turbine.

Steltz et. al [48] using his on site measurements has reported the presence of condensate containing high concentrations of impurities in the region of the saturation line, suggesting that heteromolecular effects may play some role in the appearance of the liquid phase. However, it is improbable that the large droplet sizes observed could provide enough inter-phase surface area to allow further expansion to proceed close to thermodynamic equilibrium. It is very likely that, the bulk of the flow will experience homogeneous condensation when the Wilson line is reached.

Filippov et. al [47] suggested another mechanism of condensation in blade trailing edge vortices. His hypothesis was based on the fact that wake eddies shed from the trailing edge of the blade may act as the centres for premature condensation. The subsequent diffusion and deformation of the wakes in their interaction with downstream blade rows would then spread nucleation sites to other part of the flow.

The fluctuations of temperature in the main stream is considered possible by Gyarmathy [49] who suggested that some packets of steam would follow more efficient paths through the turbines than others and would consequently cool more rapidly. His theory specifically refers to superheated flows. Subsequently, Moore et. al [50], conducted nozzle experiments using a grid in the inlet plane to generate turbulence, and found practically identical pressure distribution and droplet sizes with and without the grid. They therefore concluded that, flow fluctuations as suggested earlier were unlikely to be responsible for early nucleation. This effect has been further investigated by Bakhtar and Heaton [51] for nucleating flows in steam turbines. They suggested that some of the packets may supercool sufficiently to nucleate when the average flow has still not attained this condition. By considering the behaviour of a large number of fluid packets they found that although the droplet characteristics of the largest population agreed reasonably with the solutions for the mean flow, the population contained a sufficient proportion of larger droplets to account for the higher deposition rates. It should be noted that the turbulent motion produced by a grid within the low velocity inlet fluid, may not be representative of the intense vortices generated by the high velocity at transonic blade trailing edges. Moore later, argued that, early nucleation in turbines occurs on the curved surface of blade due to over-expansion and the nuclei formed can spread out to other regions to seed the flow, thus providing centres for condensation.

It has also been suggested that, unsteady flow due to super-critical heat addition may be responsible for increased loss due to boundary-layer separation and may even be responsible for blade failures in turbines. Due to the complexity of the problem, no evidence has been offered, and it is not known whether the phenomenon occurs in two and three-dimensional flows. The problem was investigated both theoretically and experimentally by Skilling [52] on a cascade of blades under supercritical condition. His experiment included high speed Schlieren Photographic observations which clearly showed shock oscillations. However, it is not clear whether the unsteadiness was due to supercritical heat addition, or due to some other mechanisms, such as shock boundary-layer interaction or condensation and trailing edge shockwave interaction. Furthermore, he was unable to perform tests with entirely dry flow in order to isolate condensation induced oscillations from other forms of unsteadiness.

Measurements on a cascade of rotor tip-section blades performed by Deich et. al [53] also showed oscillations which they attributed to super-critical heat addition. However, the blade profile used has very low camber angle and their cascade merely resembles a series of inclined one-dimensional nozzles and thus does not provide a good means of studying two-dimensional effects.

Denton [54] has pointed out some basic mechanisms of losses in turbomachines by relating it to the 'entropy generation'. In his concluding remarks, he commented that attempts to oversimplify the loss mechanisms in order to fit quantitative theories to them have hindered progress in this field in the past.

It is evident that many problems remain and further investigations in this area are necessary. At the University of Birmingham, significant effort has been devoted to the studies of condensation effects through the development of experimental facilities and relevant theoretical investigations. The following section will review the progress of the experimental aspect of this work.

6.0 EXPERIMENTAL INVESTIGATIONS OF TWO-DIMENSIONAL CONDENSING FLOW

Two dimensional cascades are widely used for the study of blade-to-blade flows especially when air is used as the working fluid. Cascades are also used widely for the study of steam over turbine blading when the working fluid is superheated. However, experimental observation of turbine flows in two-dimensional two-phase cascades have been limited due to the difficulty of producing nucleating and wet conditions in steady state tunnels. Under steady state conditions it is difficult to reproduce turbine wet steam conditions because the supercooling associated with the first reversion of steam is substantial. In steady flow conditions nucleation occurs in supersonic flows. This is in contrast to turbines, where because of the work extraction by the moving blades, steam can supercool sufficiently to nucleate without having to attain the speed of sound. To reproduce turbine nucleating and wet steam conditions realistically requires a supply of supercooled steam. This can be generated under blow-down conditions.

A uniquely and complex facility employing this principle has been successfully constructed in the School of Manufacturing and Mechanical Engineering of the University of Birmingham. Here, by charging a large receiver with saturated steam and then venting to a condenser, the steam is expanded in much the same way as in a cloud chamber, so a reservoir of supercooled steam is generated. This can then be passed to the test section.

Shojaee-Fard [55] and Siraj [56] studied the characteristics of the first nozzle profile in nucleating flows. The experimental observations consisted of extensive sets of static surface pressure measurements, flow visualisations and measurements of droplet size. The wake traverses on the cascade of stator blades and investigation of the characteristics of the rotor blades in superheated and nucleating steam were carried out by Ebrahimi [57]. Taking the first nozzle profile as typical, surface pressure distributions in superheated and nucleating flows indicated that the pressure distributions on the blade pressure surface were almost identical. But, there was departure between the two distributions on the suction surface. There was generally some over-expansion on the suction surface with both profiles which interacted with the zone of rapid condensation. In particular the nucleating test with subsonic outlet carried out on the stator profile showed evidence of increased aerodynamic losses. It was thought possible that the performance of the blade could be improved by modification of the profile.

Mashmoushy [58] extended the work by carrying out measurements of surface pressure distributions and flow traverses downstream of the cascade of the same rotor blade under wet steam conditions. In order to produce wet steam with prescribed droplet sizes, the inlet passage upstream of the cascade was arranged in the form of a venturi. The nucleation process was triggered by an initial expansion in the converging part and by ensuring efficient subsequent diffusion in the diverging section, the water droplets were retained.

For the blade profile investigated, when the outlet was supersonic, it was observed that the characteristics of the blade differed in superheated, nucleating and wet flows. With steam wet at inlet, the magnitude of the pressure rise observed on the suction surface just downstream of the throat was less than that obtained when steam was supercooled at inlet and decreased as the inlet wetness was increased. In the case of the tests with subsonic outlet the observed distributions were very similar under superheated, nucleating and wet conditions. It was concluded that the loss of efficiency attributed to internal thermodynamic irreversibilities, is lower when the steam is already wet at inlet to the blading.

The investigations on the performance of the rotor blade in wet steam were continued by Rassam [59], who conducted the droplet size measurements by using light extinction and flow visualisations, which consisted of Mach-Zhender interferometry and shadowgraphy.

The second nozzle profile was designed following the study of the first. The investigation by Mamat [60] was undertaken to study the effect of the changes in the profile on its nucleating characteristics.

Thus apart from the findings of the individual investigations, it has been demonstrated that nucleating and wet steam conditions experienced in turbines can be reproduced satisfactorily. The experimental measurements have also been of value in validating the theoretical treatments developed.

7.0 CONCLUSION

In view of the importance in increasing overall efficiency of low pressure steam turbine operation it is therefore a pre-requisite to understand this basic phenomenon in order to overcome its consequences due to overdesign or underdesign factor. A better knowledge of thermodynamics principles need also be incorporated in solving problems theoretically. Theoretical solutions can also be interpreted and improved design condition of steam turbine blading in due course as the problem arises can be theoretically modelled.

Nomenclature

A	Area	m^2; ft^2
C_V	Specific heat of vapour at constant volume	kJ/kg.K; BTU/lb.°R
C_P	Specific heat of vapour at constant pressure	kJ/kg.K; BTU/lb.°R
d_e	Equivalent diameter	m; ft
Ma	Mach number	-
m	Mass flow rate or mass of molecule	kg/s; lb/s or kg; lb
P	Static pressure	kN/m^2; lbf/ft^2
$P_S(T_G)$	Saturation pressure at temperature T_G	kN/m^2; lbf/ft^2
S	Supersaturation ratio ($P/P_S(T_G)$)	-
T	Temperature	K; °R
ΔT	Supercooling	K; °R
V	Overall velocity	m/s; ft/s
V_m	Velocity gradient	-
v	Specific volume	m^3/kg; ft^3/lb
w	Wetness fraction	-
μ	Dynamic viscosity	kg/m.s; lb/ft.s
ρ	Density	kg/m^3; lb/ft^3
$\rho_S(T_L,r)$	Density corresponding to saturation pressure at temperature T_L over a surface of curvature r	kg/m^3; lb/ft^3
σ	Surface tension	N/m; lbf/ft
ν	Kinematics viscosity	m^2/s; ft^2/s

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