

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

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ABSTRACT

In the operation of steam turbine, it has been well understood that the presence of two-phase flow due to condensation usually experienced by the low pressure stage. The increase of wetness percentage in the steam turbine could cause direct reduction in the overall efficiency of steam turbine. The significance of the steam turbine in the present day society is obvious when it is considered that over 80 % of the world's power is generated using steam driven turbines in either fossil fuelled or nuclear power stations. Despite this central position, little attention appears to have been devoted to the study of the problems associated with the operation and design of these machines in comparison with that given to other prime movers. Considerable effort has been spent on the investigation of flow in gas turbines and many of the findings are equally applicable to the dry. This first part of the nucleation theory will provide brief introduction into the formulation of condensation study in the steam turbine operation. The final part of the study will be given in the separate paper of Part II.

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 Early Investigations

The first theoretical expression recognising the existence of supersaturation in steam was developed by Sir William Thomson [1] (later to become Lord Kelvin). To explain the rise of liquids in capillary tubes, he derived the expression establishing the relationship between the radius of curvature of a liquid surface and the equilibrium vapour pressure adjacent to it. In the following year, in the Proceedings of the Royal Society of London, James Thomson [2] commented that:

“.....When we find a substance capable of existing in two fluid states different in density and other properties while the temperature and pressure are the same in both, and when we find also that an introduction or abstraction of heat without change of temperature or of pressure will effect the change from the one state to the other, and also find that the change either way is perfectly reversible, we speak of the one state as being an ordinary gaseous, and the other as being an ordinary liquid state of the same matter..... ..The principle that the particles of a substance when existing all in one state only, and in continuous contact with one another, or in contact only under special circumstances with other substances, experience a difficulty of making a beginning of their change of state, whether from liquid to solid, or from liquid to gaseous, or probably also from solid to liquid.....”

His statement suggests the possibility of coexistence of two-phase state in a single matter within similar temperature and pressure. He also proposed that supersaturated steam could be developed in vapour expansions. In supporting his argument, he suggested an arrangement of apparatus comprising a piston and vessel, maintained at a temperature slightly in excess of that of the initially saturated steam to be expanded inside. He further suggested the existence of what was later called *supersaturation* in vapour expansions.

von Helmholtz [3] and Gibbs [4] working independently, made fundamental studies of the principles governing the equilibrium of thermodynamics systems, and their criteria can be used to obtain Kelvin's equation. This expression is now widely known as the Kelvin-Helmholtz or Gibbs-Thomson equation.

The first known experimental observation of condensation was carried out by Aitken [5] who passed saturated steam into two separate glass vessels one containing ordinary air and the other air filtered by means of cotton wool. He noticed that the vessel containing clean air remained clear, in contrast to the one with unfiltered air in which a dense fog was formed. This was due to heterogeneous nucleation in which dust particles in the unfiltered air had acted as centres of condensation.

The first experimental observation of homogeneous and spontaneous condensation was carried out by von Helmholtz [3]. He reported that, in the absence of dust or ions, steam emerging from an orifice into clean air fogged some distance downstream of the outlet. He also discovered that an increase in the density of the observed fog resulted by having an electrical discharge in the jet of steam.

It was, however, Wilson [6], in his famous cloud chamber experiment, who laid the foundation for understanding the phenomenon of supersaturation. By performing an experiment using a glass cylinder and piston to expand moist, dust free air, he observed that if air saturated with water vapour was suddenly expanded, in the absence of foreign nuclei, at low degree of supercooling condensation did not occur. To quantify the departure of the system from equilibrium, he formulated the ratio of the vapour pressure,

P , to the saturation pressure corresponding to the local vapour temperature, $P_s(T_G)$, and termed it the supersaturation ratio, S : -

$$S = \frac{P}{P_s(T_G)} \quad (1)$$

From observations in his cloud chamber, he reported that the expansion of supercooled vapour could continue up to a maximum supersaturation ratio of 7.9 at a vapour temperature of -16°C , beyond which point, a heavy cloud resulted. Supercooling is defined as : -

$$\Delta T = T_s(P) - T_G \quad (2)$$

where T_G is the vapour temperature and $T_s(P)$ is the saturation temperature at pressure P . In order to obtain dust free air, Wilson adopted a purging process by means of repeated expansions, replacing the moisture lost as successive heterogeneous nucleation washed alien material out of the air. In his classic work, Wilson used the supersaturated vapour to visualise the paths of ionised particles as trails of condensation were formed around them.

The consequences of supersaturation were not recognised by the engineering community until some years after Wilson's cloud chamber work. Rateau [7], Bendemann [8], Loschge [9] and Henderson [10] were among the first workers to investigate the steady flow of steam through convergent-divergent nozzles. At that time, it was assumed that the discharge of steam in nozzles occurred in a state of thermodynamic equilibrium. They conducted numerous and carefully controlled tests, and found that the discharge of initially dry steam in nozzles exceeded the calculated values by 2 to 4 percent even when frictional losses were neglected. The calculations were based on a condition law which assumed the steam to remain in thermodynamic equilibrium and used the isentropic index due to Zeuner [11]. Henderson [10] also reported that the discharge of steam in nozzles, expanding in the wet region of the Mollier chart was 5 percent greater than the value expected from equilibrium calculations.

In a discussion of Henderson's work, Stodola [12] cited Bendemann's experiments demonstrating that initially dry saturated and completely dry steam showed the same tendency. Stodola attributed this discrepancy in mass flow to supersaturation of the steam undergoing rapid expansion in nozzles.

Martin [13] was perhaps the first to comment that the failure of steam to condense might be of some significance in the design of steam turbines and attempted some simple calculations to estimate the loss in a five-stage velocity compounded turbine.

Further experiments regarding condensation were performed by Callender [14] and by Stodola [12] in order to provide detailed observations of the effect of supersaturation in nozzles and estimated the resulting droplet sizes using the Kelvin-Helmholtz equation. Martin [13] then, using Wilson's data, calculated the limiting supersaturation ratios at other pressures by assuming the droplet sizes to remain constant at all conditions and plotted his results on the Mollier diagram and called the locus the Wilson line.

Mellanby and Kerr [15] weighed and analysed the flow of saturated steam through nozzles and concluded that, to account for their experimental results, supersaturation must exist. A comprehensive summary of the state of knowledge at the time, including the results of his own experimental work on the subject were published by Stodola in 1927 [12].

Another phase of research into condensation in flowing steam started in the 1930's. Yellot [16] and Yellot and Holland [17] performed detailed pressure measurements using

convergent-divergent nozzles to locate the position of the onset of condensation more precisely and found the Wilson line to be located on 4.5 percent constant moisture line on the Mollier diagram.

Rettaliata [18] performed a series of measurements using rough and smooth nozzles and demonstrated that the condition of the nozzle and the rate of expansion affected the limiting supersaturation. The lower expansion rate in the rough nozzle, resulted in the Wilson line lying closer to the saturation line than was obtained with the smooth nozzle. He concluded that the limiting supersaturation ratio was not unique and depended on the expansion rate and the initial conditions and proposed that the Wilson line should be replaced by Wilson zone. This zone covered the range from 2 percent to 4 percent wetness on the Mollier diagram and was based on the limiting values found in his experiments.

Following these investigations, Binnie and Woods [19] carried out a series of careful and reliable measurements in a de Laval nozzle. In particular, they investigated the sharp rise in pressure observed in the supersonic region downstream of the throat caused by the release of latent heat by condensation. Binnie and Green [20], continued the work by developing an electrical device to detect the onset of condensation in flowing steam and reported that the position of limiting supersaturation was dependent on the steam conditions at inlet.

Research into condensation was also driven by a problem encountered in a seemingly unrelated field. In the early days of aerodynamics, the effect of the presence of humidity in the air on the flow in supersonic wind tunnels was not appreciated. Hermann [21], noticed that the position of the shock was a unique function of air humidity. It was subsequently found that, the pressure rise was caused by the condensation of water vapour present in the flow and became known as condensation shock. Hermann's work was subsequently followed by many other investigators including Lukasiewicz and Royale [22], Head [23], Smolderen [24], Wegener and Mack [25] and Stever [26].

In parallel with the experimental investigations described above, a theory to describe the nucleation process was being pursued. The following section will briefly outline the evolution of this theory.

2.2 Evolution of Nucleation Theory

The development of the nucleation theory can be said to have been started by Volmer and Weber [27]. They suggested that the number of molecular clusters of critical size was related to the number of monomers in a system by the Boltzmann distribution law. By considering the rate of molecular collisions with the droplet surface and assuming that the growth and decay of the droplet had equal probabilities, they were able to obtain an expression for the nucleation rate.

By considering the kinetics of molecular interactions and treating nucleation as a quasi-steady process, a year later, Farkas (and Slizard) [28] obtained an expression for the nucleation rate that was consistent with Volmer and Weber's result. Based on this kinetic scheme, many other workers such as Becker and Doring [29], Zeldovich [30] and Frenkel [31] continued the development. Frenkel [31] also considered the statistical thermodynamic aspects of the problem.

The quasi-steady nucleation concept is realistic only if the time taken to achieve a steady state is small compared with the characteristic time of the process that is involved in the nucleation. Contributions to the study of transient phase have been made by Zeldovich [30], Kantrowitz [32], Wakeshima [33] and Courtney [34]. An exact analytical solution of the time-dependent nucleation equation was obtained by Kashchiev [35].

The nucleation theory just described is now commonly known as the classical nucleation theory. An excellent review of this theory giving a graphic account of the thermodynamic and kinetic aspects of nucleation is given by McDonald [36].

The second approach which has been used in the study of nucleation is the statistical mechanical approach. This has generally been used in an effort to remove some of the uncertainties which undermine the classical theory. The most notable uncertainties are perhaps, the surface tension of small clusters and the condensation coefficient. In this approach, the nucleation process is analysed at the microscopic level by applying theories of statistical mechanics. This approach is linked with the names of Bijl [37], Band [38] and Frenkel [31]. The complexities of this approach will not be discussed in this work but a comprehensive treatment of the subject is given by Dunning [39].

In 1962, Lothe and Pound [40] claimed that the classical theory neglects important terms in the free energy of formation of clusters. They argued that clusters of molecules taken as a whole possess degrees of freedom in addition to those associated with the individual molecules. These degrees of freedom are associated with the translation and rotation of the cluster. The inclusion of the free energy terms associated with these degrees of freedom in the expression for the free energy of formation of a molecular cluster, results in nucleation rates 10^{17} higher than previously obtained. This high value of nucleation rate is not in accordance with experimental findings. This treatment has been refuted by Dunning [40], Reiss and Katz [41] and Wegener and Wu [42], who have shown that experiments confirming the Lothe and Pound model can be explained by the presence of impurities.

The classical nucleation rate together with corrections due to Courtney [34] and Kantrowitz [32] can be adopted to form the formulation.

The early experimental work to study the nucleation process has tended to be in cloud chambers by pure scientists while engineers have preferred using convergent-divergent nozzles. These two approaches will be briefly reviewed.

Employing a similar cloud chamber to Wilson's Volmer and Flood [43] used an electrical field to remove ions, which might cause heterogeneous nucleation and reported good agreement with the prediction based on the Becker-Doring equations. A number of problems are inherent in the unsteady nature of piston cloud chamber experiments. Because supersaturation changes rapidly during this experiment the time associated with each condition is limited. For this reason it has proved difficult to differentiate between homogeneous and heterogeneous nucleation. Furthermore as the vapour expands its temperature drops below that of the vessel walls resulting in heat transfer and the creation of pressure and temperature waves within the vapour.

The transient operation and complicated fluid dynamics of the piston cloud chamber was replaced with a steady diffusive flow of vapour, in an inert carrier gas, between a heated pool of liquid and a cooled surface by Langsdorf [44]. This has been named as diffusion cloud chamber. Somewhere between the two surfaces supersaturation reaches its critical value and a fog forms due to homogeneous nucleation. This technique has been employed by Katz and Ostermier [45] to study homogeneous nucleation in several substances including water vapour carried in hydrogen and they reported good agreement with the classical nucleation theory.

Refinements to expansion cloud chambers have been carried out by workers such as Frey [46] and Madonna et. al [47]. Investigators using diffusion cloud chambers have, in general, reported better agreement with classical nucleation theory.

3.0 CONDENSATION IN NOZZLES

By virtue of its simplicity and reliable performance in representing one-dimensional flows, the majority of engineering investigations into the effect of condensation in flowing steam have been carried out using convergent-divergent nozzles. These have also proved useful in validating nucleation and droplet growth theories.

Nozzle experiments are performed under steady state conditions and the whole history of the condensation process is conveniently displayed spatially along the length of the nozzle. Instead of relying on the visual observation of fog to determine the onset of nucleation, it can be easily detected from the measurement of pressure in nozzle experiments. The relatively rapid expansion in the nozzle allows little time for heat transfer from the apparatus to the working fluid and also weakens the effect of undesirable heterogeneous nucleation which has been shown to be negligible by *Stodola* [12].

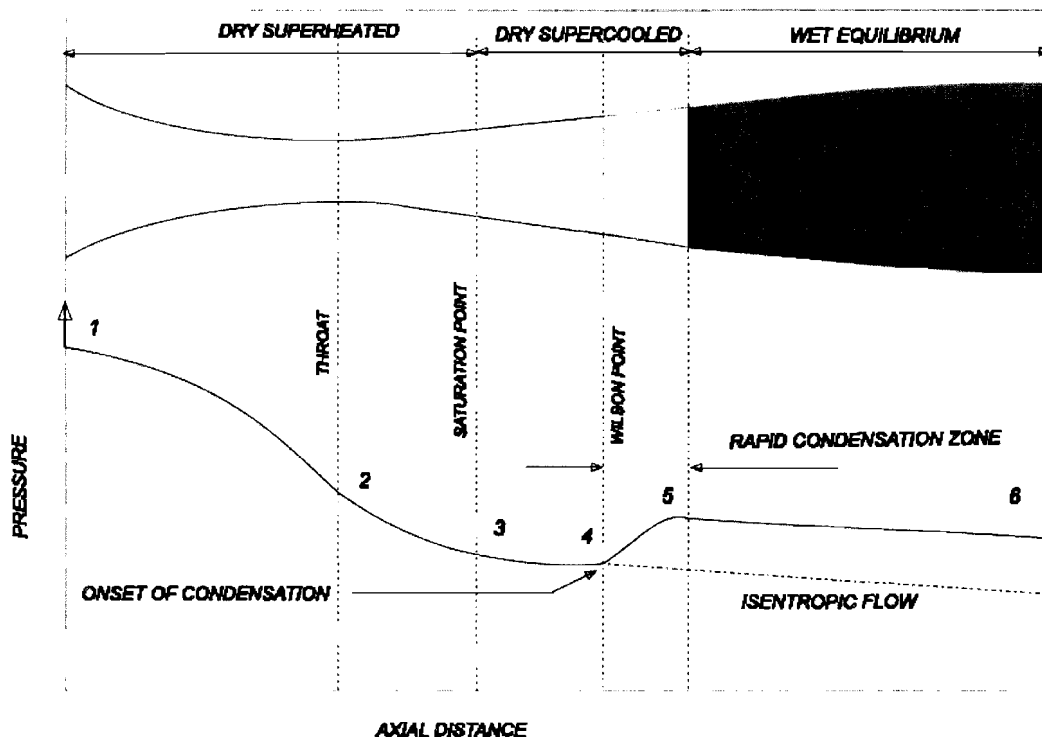


Figure 1 Axial pressure distribution in a nozzle with spontaneous condensation

Depending on the local conditions and rate of expansion (Figure 1), nucleation rate increases dramatically and reaches its maximum at point (4), where breakdown of supersaturation occurs. The region just upstream of point (4) is termed the nucleation zone and is terminated by the Wilson point (4), which is the point of maximum supercooling. Downstream of this point, nucleation effectively ceases and the number of droplets in the flow remains constant. The nuclei grow rapidly between points (4) and (5) by exchanging heat and mass with the surrounding vapour and restore the system to near thermodynamic equilibrium. The conduction of latent heat, which is released at the droplet surfaces, to the parent vapour, gives rise to a gradual increase in pressure from point (4) to (5) known as condensation shock and decelerates the already supersonic flow. The term condensation shock is, however, misleading because the changes of flow properties between these points are continuous. Since the heat transfer takes place through

finite temperature difference between the phases, the process is essentially irreversible and has associated with it a net rise in entropy from point (4) to (5). This is referred to as Thermodynamic Nucleation Loss. Further expansion of the flow between points (5) and (6) takes place close to equilibrium.

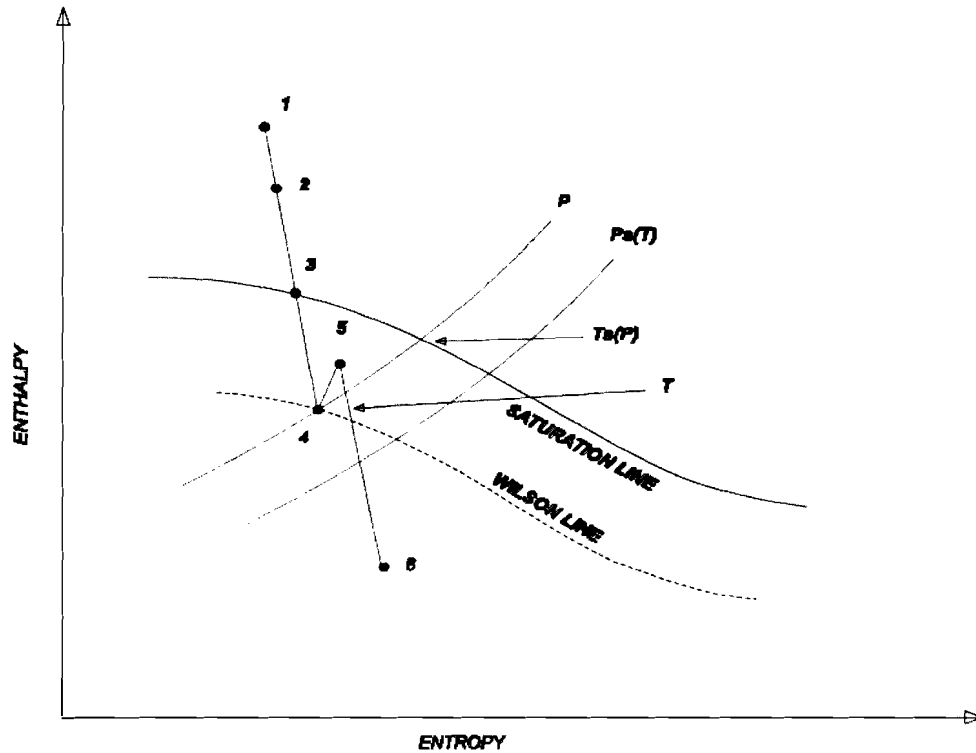


Figure 2 State line for expanding steam with spontaneous condensation

The observed phenomena resulting from condensation in flowing steam in nozzles and the development of treatments to describe them will be discussed in the following sections. A typical condensing flow of steam in a convergent-divergent nozzle is shown schematically in Figure 1. The path of the expansion is shown on the *Mollier* diagram in Figure 2. Steam expands from initially dry-superheated stagnation state (1) to sonic conditions at the throat (2). The state path crosses the saturation line and droplet embryos begin to form and grow in the vapour at point (3). The nucleation rates associated with these early embryos are so low that the steam continues to expand as a dry single-phase vapour in a metastable, supercooled or supersaturated state.

4.0 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

P	Static pressure	$\text{kN/m}^2; \text{ lbf/ft}^2$
$P_s(T_G)$	Saturation pressure at temperature T_G	$\text{kN/m}^2; \text{ lbf/ft}^2$
S	Supersaturation ratio ($P/P_s(T_G)$)	-
$T_s(P)$	Saturation temperature at pressure P	K; °R
ΔT	Supercooling	K; °R
T_G	Vapour temperature	K; °R

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