International Journal of Thermal Sciences 132 (2018) 435–445

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Effect of wall surface roughness on condensation shock

Aditya Pillai*, B.V.S.S.S. Prasad

Turbo Machines Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India

ARTICLE INFO

Keywords:
Condensation shock
Surface roughness
Boundary layer
Non-equilibrium
Wet steam
Nozzle
Two-phase flow

ABSTRACT

The effect of sand grain type surface roughness on an unseparated incipient condensation shock and its influence on the boundary layer has been studied numerically for wet steam supersonic flow in a Laval nozzle. In the vicinity of the condensation shock, the sudden jump in density and a reduction in the wall shear stress causes a rapid drop in skin friction. The pressure shows a mild adverse gradient in this region. The boundary-layer velocity profiles vary with roughness value at a constant inlet pressure. The boundary layer thickness increases with the increase in either the inlet pressure, or the size of the roughness elements. As the roughness height is varied from 1 μm to 1000 μm the boundary layer thickness increases typically by 33% whilst the peak value of pressure gradient drops down by 50%. The boundary layer thickness is found to be maximum for p_o = 80 kPa owing to secondary nucleation. The peak value of pressure gradient is noticed to be doubled as the flow medium changes from dry air to wet steam.

1. Introduction

In the last few stages of steam turbines with large power output, the presence of wet steam influences the condition line crossing over into the two-phase region. As this happens, condensation takes place, not as soon as it crosses the saturation line, but only after it has attained some degree of supercooling. The point at which the liquid droplets are formed is called the Wilson point. The steam is in metastable state and the condensation occurs in non-equilibrium. Latent heat is released from liquid water as the phase change occurs and this heat has to be taken over by the surrounding vapour phase. This raises the temperature of the vapour which in turn increases its pressure. This sudden increase in pressure formed due to condensation, is called condensation shock. Fig. 1 shows the pressure variation along the nozzle of Moses and Stein [1] (a) when the working medium is dry air and (b) when it is wet steam. The two curves in Fig. 1 portray the relative effect of condensation shock on the flow phenomenon.

After the condensation shock the steam generally reverts to near thermodynamic equilibrium where the temperatures of both the vapour and the droplets are close to the saturation level. Since the growth of liquid phase takes place by heat transfer through finite temperature difference between the phases, the process is essentially irreversible. The net rise in entropy that appears as a reduction in the potential for performing work can be equated to thermodynamic wetness loss, a reason for loss in turbine efficiency.

If the degree of subcooling is increased further, an aerodynamic shock wave may be formed inside the condensation zone. Inlet subcooling in the present study does not exceed this limiting value and the pressure rise observed here is gradual, so it can be said that the flow is independent of any aerodynamic shock and only condensation shock can be seen. The presence of condensation leads to problems of blade erosion and losses in turbine efficiency. Wet steam two-phase condensing flows usually occur in the supersonic flow conditions.

Condensation shock is a major feature of the non-equilibrium condensation phenomenon. Condensation shock represents nucleation of droplets in the flow and their subsequent growth. Of the three main components of wetness loss, thermodynamic losses are associated with the irreversible heat transfer between the two phases during condensation. Numerical studies are performed with an attempt to capture condensation shock and to estimate the thermodynamic losses [2]. Emphasis on condensation shock to alleviate the wetness losses have been made. Parametric studies have been conducted to determine what influences condensation shock and how these strategies can be implemented to reduce the thermodynamic losses. At first, the necessary conditions for the existence of condensation shocks were studied [3] and further efforts were made to control and suppress condensation shocks [4–6]. Shock strength reduction indicates a reduction in entropy and hence thermodynamic losses. It is important to study the influence of different parameters on non-equilibrium condensation so that losses can be estimated and mitigated more accurately. However, the effect of surface roughness on non-equilibrium condensation has not been studied yet.

During the operation of steam turbines, the blade surfaces experience severe performance degradation. Erosion of blades due to heat,

* Corresponding author.
E-mail address: adityapillai009@gmail.com (A. Pillai).

https://doi.org/10.1016/j.ijthermalsci.2018.06.028
Received 26 October 2017; Received in revised form 28 January 2018; Accepted 21 June 2018

Nomenclature

C_f	Skin friction coefficient
C_μ	Constant in modelling turbulent viscosity
C_S	Roughness constant
C.V.	Control Volume
co	Speed of sound
$D\omega$	Cross diffusion term
E	Total Energy per unit mass
G_k, G_ω	Generation term for k and ω
H	Total Enthalpy
h_{lv}	Specific enthalpy of evaporation at pressure p
I	Nucleation rate
Ks^+	Non-dimensional roughness height
Ks	Equivalent sand grain roughness
k	Turbulence kinetic energy
L	Nozzle Length
M_m	Mass of 1 molecule
$\dot{P}$	Expansion rate
p	Local Pressure
p_o	Inlet Total Pressure
p_{out}	Static pressure at exit
q_c	Evaporation coefficient
$\bar{r}$	Average radius of droplet
r*	Critical droplet radius
S	Super saturation ratio
S_k, S_ω	User defined source terms for k and ω
T_o	Inlet stagnation temperature
T_d	Droplet temperature
T_G	Vapour temperature
T_R	Reduced temperature
u_p	Velocity parallel to the wall
u*	Friction velocity
u^+	Non-dimensional height, up/u*
V_d	Average droplet volume
x	Axial distance
Δx	Minimum cell width
Y_k, Y_ω	Dissipation term for k and ω due to turbulence
y_p	Distance from the wall
y^+	Non-dimensional height, (u*.y/ν)
y	Height
Δy	Minimum cell height

Greek symbols

β	Mass fraction of condensed liquid phase
δ	Boundary layer thickness
η	Number density of droplets per unit volume
Γ	Mass generation rate due to condensation and evaporation
Γ_k, Γ_ω	Effective diffusivity term for k and ω
ϒ	Ratio of specific heat capacities
κ_B	Boltzmann constant
μ	Dynamic viscosity
μ_t	Turbulent or Eddy viscosity
ν	Kinetic Viscosity
ω	Specific dissipation rate
ρ, ρ_l, ρ_v	Density of mixture, liquid & vapour phase evaluated at temperature T
σ	Liquid surface tension
θ	Non-isothermal correction factor
τ_w	Wall shear stress

(i.e., thermal erosion) the collision of particles or impurities and deposition of impurities on the blades surface significantly affect the surface roughness of the blades. A large quantity of experimental and numerical work has been done on the performance losses of turbines due to blade surface roughness.

Early investigations into the performance of wet steam turbine stages were endeavors to better understand the losses associated with non-equilibrium condensation. Experiments were performed on turbine rotor cascades and modelling approaches were examined to better predict the wet steam condensation phenomenon [7–16]. Homogeneous spontaneous condensation of steam is still being studied with an intention of increasing the last stage and overall efficiency of the turbine [17]. Since the devices in which the condensation process takes place are extremely complex, it makes it quite difficult to model and conduct numerical and experimental research. On the other hand, a simple model for simulating complex flows in practical domains is a converging-diverging nozzle. In the past, different nozzles each with different characteristics, were designed and experiments were performed to study the wet steam condensation (ex. Moore [18], Moses [1], Binnie [19], Gyarmathy [20]). Different parameters that perturb the flow physics and influence the losses were investigated.

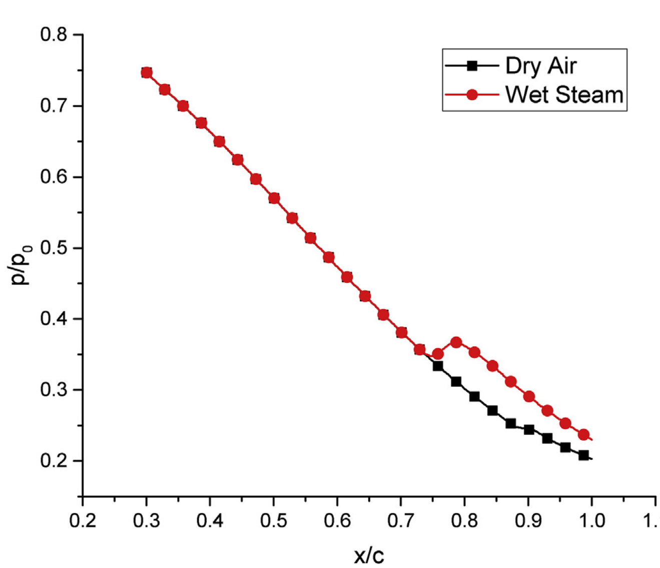

Fig. 1. Pressure variation along the nozzle length with and without shock at p_o = 90 kPa.

Early works [21,22] include the study of the structure and growth of the turbulent boundary layers once it encounters roughness and discuss the conditions that should be met for self-preservation. Liu and Squire [23] studied shock wave boundary layer interactions (SWBLIs) on curved surfaces and concluded that the critical peak Mach number does not change very much with the surface curvature and is close to 1.30. Babinsky and coworkers [24–26] conducted extensive investigations to determine the effects of surface roughness on turbulent boundary layers. The velocity profiles downstream of the roughness were found to be less full, and skin friction was reduced but no large-scale separation due to the additional effects of roughness was observed. They also found that, even for roughness heights in the hydraulically smooth regime, incoming boundary layers were thicker, and slightly less full than smooth wall profiles. Theoretical considerations also suggested an influence of surface roughness on incipient separation. The effect of irregular surface roughness on turbulent boundary layer was considered by Wu and Christensen [27] which indicate that large-scale low and high-momentum regions exist in both smooth and rough wall flows and these large-scale features contain a lot of energy and manifest a majority of the Reynolds shear stress.