CFD Analysis of Unsteady Flows due to Supercritical Heat Addition in High Speed Condensing Steam

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Graphical abstract
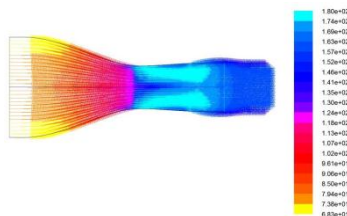
Abstract

This study is mainly to investigate the unsteady flows due to supercritical heat addition in high speed condensing steam in steam turbines. To achieve this, condensation flow characteristic is investigated on 2D converging-diverging nozzle. A Computational Fluid Dynamics (CFD) code (FLUENT package) that adopted the Eulerian-Eulerian approach for modeling wet steam flow, was used. The condensing flow is governed by the compressible Navier-Stokes equations in conjunction with a wet steam multiphase model. The turbulence model selected for this work is Spalart Allmaras model which is based on the Reynolds Averaged Navier Stoke (RANS) model available in FLUENT. Results are then compared with previous researchers that use different methods including user defined code and experiment. The importance of this research study is to determine the accuracy of the software and method used and to compare the results with other researchers.The current work shows good agreement with the experimental data done by Skilling [1] and 2D calculations done by Yusoff et al. [2]. It is found from the numerical simulation results that the supercritical heat addition has caused the flow in the condensing steam to retard and gives rise to pressure oscillations. The unsteady supercritical heat addition reveals promising results indicating the capability of FLUENT to calculate this phenomenon which might cause instability in turbine channel.

Keywords: CFD, wet steam, nucleation, supercritical heat addition

1.0 INTRODUCTION

Steam turbines are mainly built for large scale electricity generation with several low pressure stages operate in two phases; dry and wet steam. During the rapid expansion of steam, spontaneous condensation takes place shortly after the state path crosses the vapour saturation line. The expansion process causes the superheated dry steam to first subcool and then nucleates to form a two phase mixture of saturated vapour and fine droplets known as wet steam. Modeling wet steam is very important in the analysis and design of steam turbines as the increase in steam turbine exit wetness can cause severe erosion of the turbine blades at the low pressure stages. It also can reduce the thermodynamics and aerodynamics efficiency of the turbine. Since a large part of the total power output is produced by the low pressure steam turbines, predicting the steam condensing flow and understand its behaviour is of significant importance as it allows one to determine the losses and suggests how to minimise them.

It is well known in the literature that when condensation takes place near sonic conditions, periodically unsteady phenomena may result from interaction between the condensation-induced supercritical shockwave and the nucleation zone. Experimental studies were conducted for wet steam by Barschdorff [3] and Skilling [1]. Since then, a number of numerical investigations for unsteady condensation have been presented, including the

one-dimensional calculations of Skillings and Jackson [1], and two-dimensional calculations of White and Young [4]. Malek et al. [5] and Yusoff et al. [2] applied the treatment to the unsteady, one and two-dimensional flows on a cascade of nozzle blades respectively, and obtained good agreement with the experimental measurements.

In this study, two-dimensional (2D) axisymetric wet steam flow analysis through a convergent divergent nozzle is carried out with the help of CFD tools (Gambit 2.4.6 for modelling and Fluent 6.3.26 for analysis). Before performing the transient problem, a steady-state solution is generated to provide the initial values for the mass flow rate at the nozzle exit.

2.0 MATHEMATICAL FORMULATION

2.1 The Governing Equation

The condensing flow is governed by the compressible Navier-Stokes equations in conjunction with a wet steam multiphase model. To solve the problem, a CFD code (FLUENT package) that adopted the Eulerian-Eulerian approach for modeling wet steam flow, was used. The governing equations (mass conservation, momentum and energy) are stated as:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = S_m \qquad \text{(Eq. 1)}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + S_{u_i} + S_{F_i} \qquad \text{(Eq. 2)}$$

$$\frac{\partial}{\partial t}(\rho H) + \frac{\partial}{\partial x_j}(\rho u_j H) = \frac{\partial P}{\partial t} + \frac{\partial}{\partial x_j}\left[\Gamma_E \frac{\partial T}{\partial x_j}\right] + S_w + S_d + S \qquad \text{(Eq. 3)}$$

where x_i are the Cartesian coordinates; u_i are the corresponding average velocity components; t is the time; ρ is mixture density; P is pressure; τ_{ij} are stress tensor components; T is average temperature; H is total enthalpy; Γ_E is effective thermal conductivity. The term S_m is the mass source (defined to reflect the condensation and vaporization process); S_{ui} contain source representing momentum exchange between the water droplets and surrounding gas; S_{Fi} contains the smaller terms from gradient of the Reynolds stress tensor; $S_w + S_d$ represents the total viscous stress energy contribution; and S_h contains the interphase heat transfer.

2.2 Turbulence Model

The turbulence model selected for this work is Spalart Allmaras model which is based on the Reynolds Averaged Navier Stoke (RANS) model available in Fluent. This model is employed due to the reason that it has been shown in the literature to give good results for boundary layers subjected to adverse pressure gradients [6].

$$\frac{\partial}{\partial t}\int_V \rho \Phi dV + \oint_A \rho \Phi dV \cdot dA = \oint_A \Gamma \nabla \Phi \cdot dA + \int_V S_\Phi dV \quad \text{(Eq. 4)}$$

Based on Eq. 4, the first term from the left hand side of the equation is the unsteady term on 3-Dimensional for mass. The second term is the convective terms. On the right hand side of the equation, the first term is the diffusive term and lastly the source term, also known as the generation term.

3.0 MODEL DESCRIPTION

3.1 Nozzle Geometry and Boundary Conditions

Among many test cases carried out to model unsteadiness in steam condensing flow, the expansion in Skilling nozzle was presented. This nozzle is an converging-diverging nozzle with the critical throat height 87.7mm. The geometry of the nozzle was produced with Gambit 2.4.6 software. The mesh was constructed in order to follow the flow, facilitating the solution convergence. Figure 1 shows the meshed profile of Skilling nozzle. The inlet total temperature, T0 and inlet total pressure, P0 were set to be 347.9 K and 35140 Pa respectively. The numerical results were compared with experiment done by Skilling [1] and other numerical calculations [2,5].
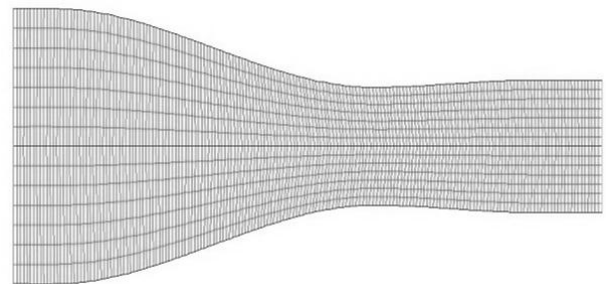

Figure 1 Meshed profile of Skilling nozzle

3.2 Test Cases

Dry steam with steady condition was first simulated. After the simulation has achieved the convergence criteria, the wet steam model with steady condition was simulated. In process of defining a transient flow, the time option in the solver was first changed to unsteady. The Second Order Implicit was selected under the unsteady formulation as which provides more accuracy in time compared to the First Order Implicit because the implicit (dual) time-stepping enabled the physical time step to be set and used for the prediction of transient flow [7],[8}. A wave-shaped profile is defined at the outlet pressure which described by the Eq. (5). The user-defined function (UDF) was written as for defining the pressure profile required equation.

$$p_{\text{exit}}(t) = 0.12 \sin(\omega t) + \overline{p}_{\text{exit}} \qquad \text{(Eq. 5)}$$

where ω is the circular frequency of unsteady pressure measure in rad/s and   is the mean pressure measured in atm.

For the iteration process of unsteady flow, the time step is critical for accurate time-dependant flow predictions. Time step used size used was 2.85596×10^{-5} seconds to obtain the requirement of 100 time steps for one pressure cycle. The iteration process was continued until the convergence criteria achieved. The iteration process was further continued by changing the multiphase model to wet steam model until the convergence criteria was achieved.

4.0 RESULTS AND DISCUSSIONS

4.1 Steady and Unsteady Flows of Dry and Wet Steam

The dry steady and unsteady flows show similar pattern in velocity and static pressure at the centre of the nozzle as in Figure 2 (a) and Figure 2 (b). This is due to the fact that no spontaneous condensation occurs and hence there is additional heat added to the flow.

However when the wet steam model is employed, the results for steady and unsteady flows are unlikely the same as seen in Figure 3 (a) and Figure 3 (b). Both results display a sudden jump in the static pressure downstream of the throat as this is the onset of condensation. Nevertheless, it is clearly seen in Figure 3 (b) that the flow was disturbed after the onset of condensation and the static pressure became unstable afterward. When comparing the flow velocity of both cases after the onset of condensation in Figure 4 (a) and Figure 4 (b), it can be seen that the velocity of the unsteady case (in Figure 4 (b)), is lower that the steady case. These may be due to the release of additional latent heat to the flow and cause the flow to retard. This additional latent heat is termed 'supercritical'.
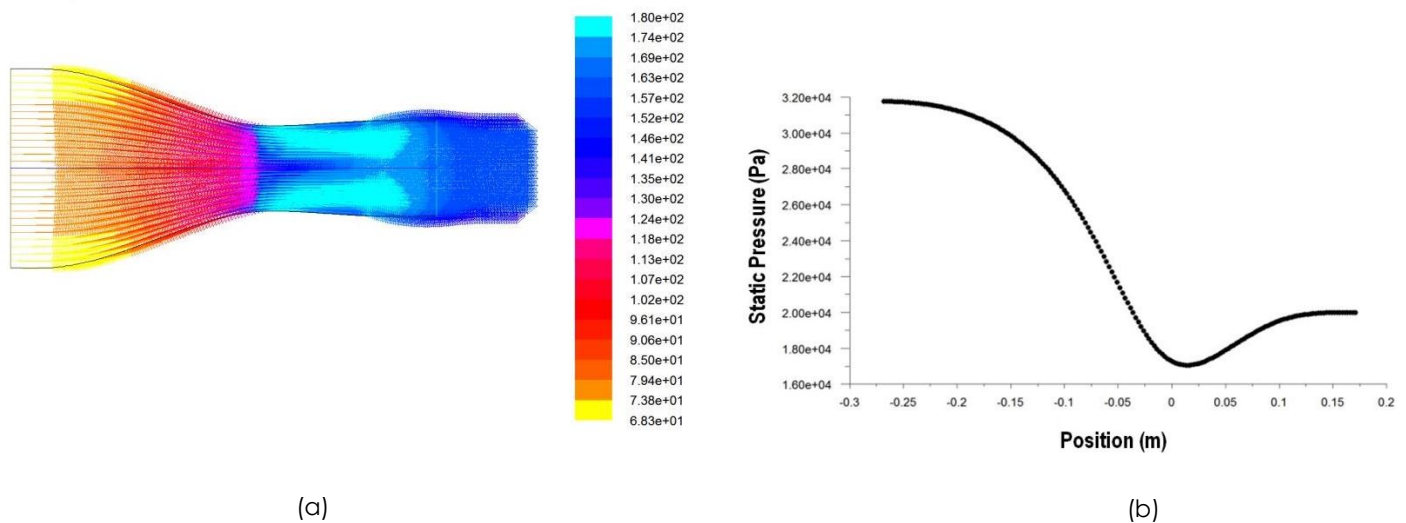

(a)   (b)

Figure 2 (a) Velocity vectors and (b) Static pressure, of steady and unsteady flows of dry steam
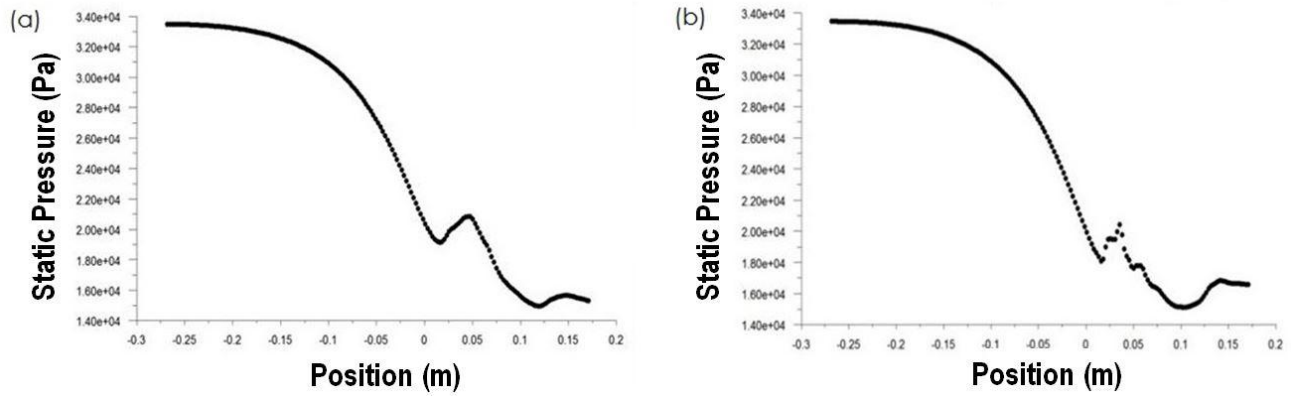
Figure 3 Static pressure of (a) Steady flow of wet steam (b) Unsteady flow of wet steam
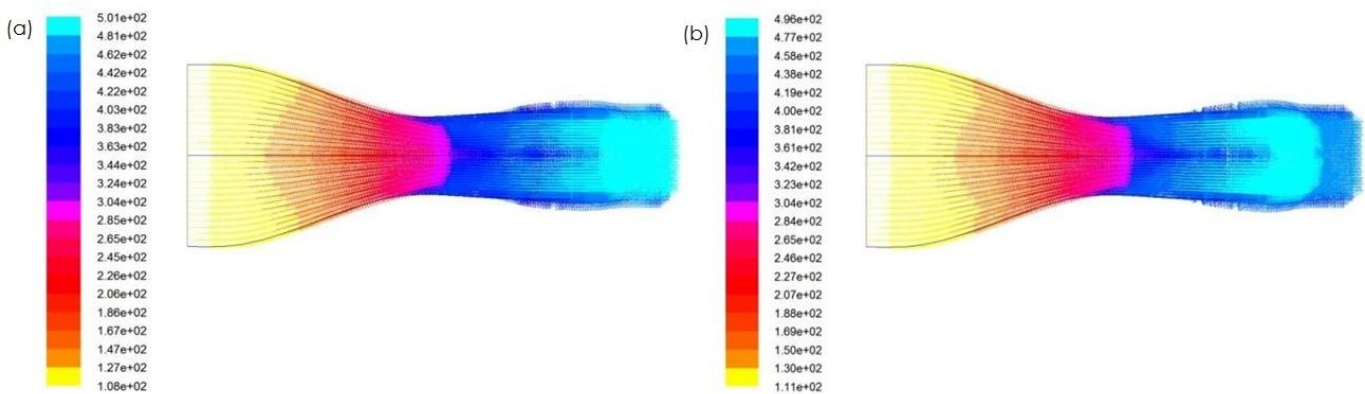

Figure 4 Contours of static pressure of (a) Steady flow of wet steam (b) Unsteady flow of wet steam

4.2 Results Comparison with Other User Defined Code and Experiment

The comparison of the static pressure results obtained in current work shows good agreement with that of 2D calculation did by Yusoff et al. [2] and experiment did by Skillings[1]. These can be seen in Figure 5 (a) and (b). The variations of static pressure at a point located just downstream of the nozzle's throat is plotted against time step as in Figure 6. As the flow becomes unstable the pressure decreases significantly and this pressure drops restores the sonic flow at the throat and gives rise to oscillations. In this study, regular oscillations with a frequency of 400 Hz was obtained. The amplitude of oscillations of about 18 mbar was also produced. The frequency and pressure difference of current results are compared with previous data obtained from other researchers and tabulated in Table 1. Based on the table, current model shows a good agreement with the other user defined code and experiment with slight difference.
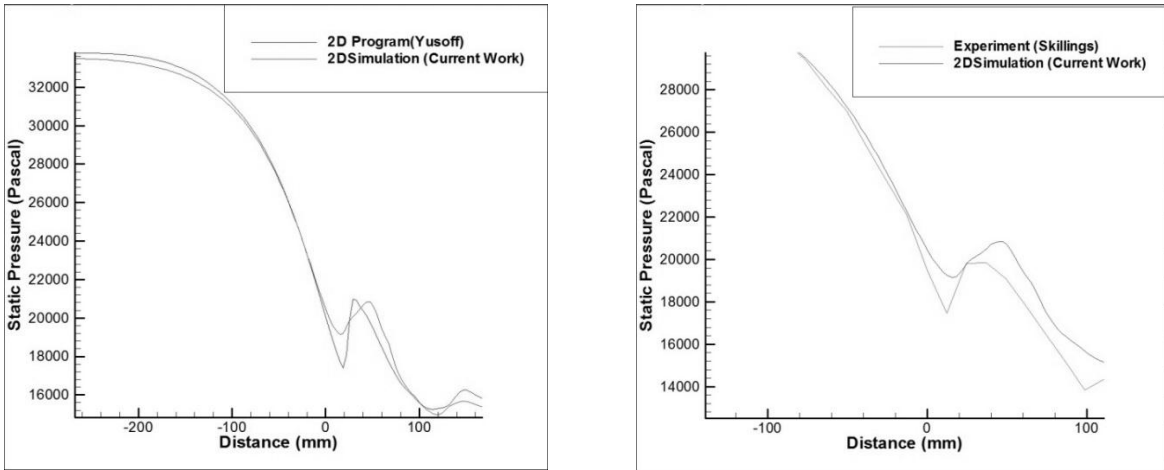
Figure 5 Comparisons with (a) 2D calculation by Yusoff et al. [2] (b) Experimental measurement by Skillings [1]
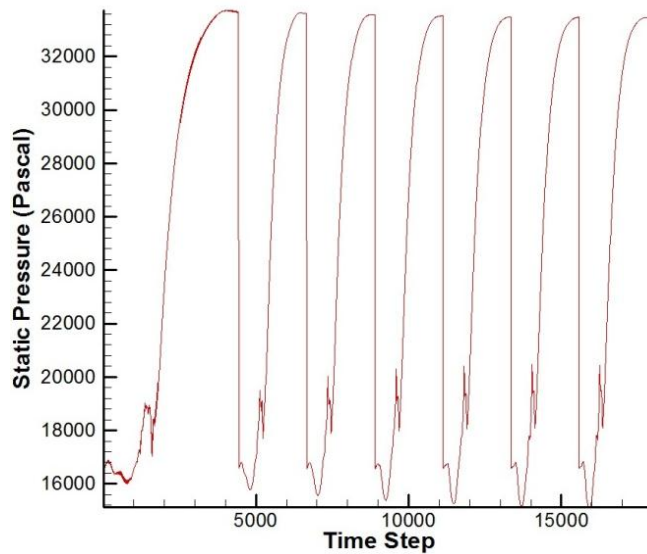

Figure 6 Static pressure downstream of skilling's nozzle throat against time step

Table 1 Comparisons of frequency and pressure difference between current work with other user defined code and experiment

Author	Case	Frequency, Hz	Pressure Difference, mbar
Skillings [1]	Experiment	380	20
Yusoff et al. [2]	2D Program	393	18
Malek et al. [5]	1D Program	302	17
Current Work	2D(FLUENT)	400	18

5.0 CONCLUSION

The unsteady supercritical heat addition reveals promising results indicating the capability of FLUENT to calculate this phenomenon which might cause instability in turbine channel. The heat addition causes the flow to retard and gives rise to oscillations. Comparison with published experiments and numerical investigations is generally good although the computed frequency and amplitude of oscillation is slightly deviated. This may be due difference method used in the calculation. It is recommended that FLUENT to be used to further simulate wet steam in turbine cascades so that the phenomenon of wet steam in steam turbine stages can be accurately.

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