The effect of coalescence on droplets size distribution in wet steam flow

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Abstract
During the crossing and rapid expansion of steam in turbines, the vapour first supercooled and then with nucleation to become a wet steam. The droplets in wet steam change their properties due to several mechanisms. The most common mechanisms are coalescence (aggregation), breakage, nucleation and growth. In this study, we model coalescence between droplets colliding with each other because of turbulent fluctuations in the surrounding continuous phase in a converging-diverging nozzle. Droplets size distribution are predicted and compared with experimental results. It is found from the numerical simulation results that by considering coalescence between droplets, their size distribution approach the experimental data. Therefore this solution could be effective in designing the steam nozzle and turbine blades.

Introduction
In steam turbines that using for the fossil fuelled power stations or gas cooled nuclear reactors [1], the wetness happened on the last few stages of the low-pressure instruments; because the fluid temperature in LP turbines decreases due to the steam expansion and also steam pressure is much higher than the saturation pressure corresponding to the flow temperature. Therefore the superheat vapour crosses the saturation line and enters the two-phase region; in the other words spontaneous condensation would be induced. In the condensation process, dry steam at first subcooled and then nucleates to form a two-phase mixture of saturated vapour and fine liquid droplets known as wet steam. The presence of a liquid phase within the turbine causes the thermodynamic, aerodynamic and mechanical losses or erosion [2].Often the expansion process and condensation phenomenon in the LP turbines can be simulated under the transonic Laval nozzle [3]. It has seen steam expansion from superheated to wet conditions in such nozzle (See Fig. 1).
Now we discuss the effect of coalescence which created by turbulent fluctuations on droplets size distribution in wet steam flow. Coalescence (aggregation) is a process where two or more particles combine together to form a large particle. The total number of particles reduces in a coalescence process while mass remains conserved (See Fig.2) [4]. Contact and collision is the premise of coalescence. The collision between droplets is usually caused by their relative velocity. The relative motion may occur due to a variety of mechanisms [5] that we consider motion induced by turbulent fluctuations in the surrounding continuous phase.

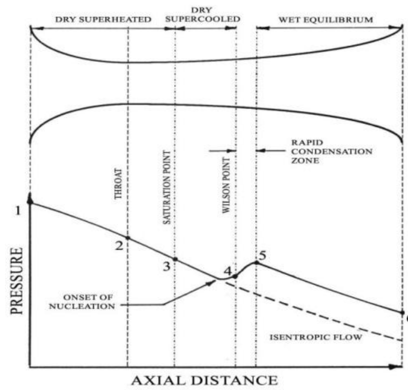

Figure 1. Variation of axial pressure for the steam expansion on the Laval nozzle centerline

Figure 2. Coalescence between two particles

Governing Equations
The temporal change of particle number density in a spatially homogeneous physical system is described by the following well known population balance equation (PBE) developed by Hulbert and Katz [4,5]:

$$\frac{\partial n}{\partial t} = S_b + S_c \tag{1}$$

$$S_b = \int_d^\infty m(d_i)\beta(d, d_i)\Omega(d_i)n(d_i, t)\,d(d_i) - \Omega(\mathrm{d})\,\mathrm{n}(\mathrm{d}, \mathrm{t})$$

$$S_c = \frac{1}{2}\int_0^V \lambda(V - V_1, V_1)h(V - V_1, V_1)\mathrm{n}(V - V_1, t)n(V, t)\,\mathrm{d}(V_1) - \mathrm{n}(\mathrm{V}, \mathrm{t})\int_0^\infty \lambda(\mathrm{V}, \mathrm{V_1})\mathrm{h}(\mathrm{V}, \mathrm{V_1})\mathrm{n}(\mathrm{V_1}, \mathrm{t})\,\mathrm{d}(\mathrm{V_1}) \tag{2}$$

source terms S_b and S_c characterize particle coalescence and breakup. The phenomenon of fluid particle coalescence has been the subject of considerable theoretical and experimental attention over the past decades. A variety of models have been published to determine the collision frequency $h(V–V_1, V_1)$ and coalescence efficiency $\lambda(V–V_1, V_1)$. For the collision resulting from the various relative velocities, different models for the corresponding frequency should be derived. Since not all collisions lead to coalescence, the concept of efficiency or probability is introduced. Therefore, the coalescence frequency Γ $(V–V_1, V_1)$ is determined by both collision frequency $h(V–V_1, V_1)$and coalescence efficiency λ $(V–V_1, V_1)$[5]:

$$\Gamma = h\,\lambda \tag{3}$$

Collision frequency and coalescence efficiency was derived by Prince and Blanch (1990) as below [5]:

$$h(d_1, d_2) = C_1'(d_1 + d_2)^2(d_1^{2/3} + d_2^{2/3})^{1/2}\varepsilon^{1/3} \qquad \text{where } C_1' \text{ is in the range 0.28-1.11} \tag{4}$$

$$\lambda = \exp\left(-\frac{\rho_c^{\frac{1}{2}} r_{eq}^{\frac{5}{6}} \varepsilon^{\frac{1}{3}} \ln\left(\frac{h_i}{h_f}\right)}{4\sigma^{\frac{1}{2}} r_{ij}^{\frac{2}{3}}}\right) = \exp\left(-C_{16}' \frac{\rho_c^{\frac{1}{2}} r_{eq}^{\frac{5}{6}} \varepsilon^{\frac{1}{3}}}{\sigma^{\frac{1}{2}}}\right), r_{eq} = \left[\frac{1}{2}\left(\frac{1}{r_1} + \frac{1}{r_2}\right)\right]^{-1}, h_i = 10^{-4}, h_f = 10^{-8}, C_{16}' = \frac{\ln(\frac{h_i}{h_f})}{4} = 2.3 \tag{5}$$

Scott [6] provided a number of solutions of PBE for a variety of initial conditions and three types of coalescence kernel(coalescence frequency).So droplets size distribution can be calculated in wet steam flow.

Results

Coalescence between droplets, colliding with each other because of turbulent fluctuations in the surrounding continuous phase, has been investigated in wet steam flow. Droplets size distribution are predicted and compared with experimental results in fig 3. It is found from the numerical simulation results that by considering coalescence between droplets, their size distribution are in a good agreement with the experimental results. Therefore this solution could be effective in designing the steam nozzle and turbine blades.

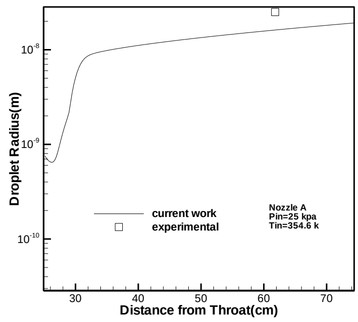

Figure 3. Theoretical and experimental data of droplet radius in center line of nozzle.

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