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A numerical study on turbulence attenuation model for liquid droplet impingement erosion

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ABSTRACT

The bent pipe wall thinning has been often found at the elbow of the drain line and the high-pressure secondary feed-water bent pipe in the nuclear reactors. The liquid droplet impingement (LDI) erosion could be regarded to be one of the major causes and is a significant issue of the thermal hydraulics and structural integrity in aging and life extension for nuclear power plants safety. In this paper two-phase numerical simulations are conducted for standard elbow geometry, typically the pipe diameter is 170 mm. The turbulence attenuation in vapor-droplets flow is analysed by a damping function on the energy spectrum basis of single phase flow. Considering the vapor turbulent kinetic energy attenuation due to the involved droplets, a computational fluid dynamic (CFD) tool has been adopted by using two-way vapor-droplet coupled system. This computational fluid model is built up by incompressible Reynolds Averaged Navier–Stoke equations using standard k–ε model and the SIMPLE algorithm, and the numerical droplet model adopts the Lagrangian approach, a general LDI erosion prediction procedure for bent pipe geometry has been performed to supplement the CFD code. The liquid droplets diameter, velocity, volume concentration are evaluated for the effects of carrier turbulence attenuation. The result shows that carrier turbulence kinetic energy attenuation is proved to be an important effect for LDI erosion rate when investigating the bent pipe wall thinning phenomena.

1. Introduction

In the area of power engineering industry safety analysis, the bent pipe wall thinning has been often found in nuclear power plants as well as the fossil power plants. For example, JSME annual report records one accident that the rupture pipe is located as Figs. 1a and 1b show, the small hole and flow direction is also depicted in Fig. 2 (JSME, 2007). In order to estimate the residual lifetime of pipes and to provide the proper maintenance, the liquid droplet impingement (LDI) wall thinning rate evaluation is needed. LDI erosion could be regarded to be one of the major causes of unexpected troubles occasionally occurred in the inner bent pipe surface. Evaluating the LDI erosion is an important topic of the thermal hydraulics and structural integrity in aging and life extension for nuclear power plants safety. In general, major parameters that influence LDI erosion are categorized into four groups: flow pattern, corrosive conditions, droplet impingement properties and material properties (Okada and Uchida, 2009). The droplet erosion mechanism is less well understood than particulate solid sand erosion. Droplet erosion is obviously confined to wet gas and multiphase flows in which droplets can generate. From the point of flow pattern view, erosion rate is dependent on a number of factors including the droplet size, impact velocity, impact frequency, and liquid and gas density and viscosity. As many of these values are unknown for field situations, it is very difficult to predict the rate of droplet erosion. It should also be noted that control of many of these factors in laboratory-based tests is problematical. Therefore a great deal of care should be required when extrapolating lab test results to field conditions. Hence computational fluid dynamics (CFD) can be used as a power tool to investigate the LDI phenomena.

Since it is difficult to rig in the experiment, the carrier and droplets velocity profiles and their relationships were studied numerically by the authors' previous work (Li and Merzari, 2009; Li and Ninokata, 2009, 2010). In this paper, the carrier turbulence kinetic energy investigation and its influence to LDI erosion rate was studied. The motion of particle suspended in turbulent flows is a topic of great interest whose theoretical aspects have been extensively considered by Hetsroni (1989). Due to the huge liquid particles are transported in the involved carrier, the turbulence structure of the continuous carrier was found to be affected as a result of the presence of the dispersed phase. The presence of particles

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Nomenclature

A_d	droplet cross-sectional area (m^2)
A_n	amplitude in velocity spectrum of fluid (m)
A_i	constant values
A	wall face area (m^2)
a_n	amplitude in velocity spectrum of droplets (m)
C	erosion formulation constant
C_0	drift-flux model distribution factor
C_d	drag force coefficient
d_d	droplet diameter (m)
$d(v)$	droplet impact velocity function
$E(\upsilon)$	spectrum of turbulent kinetic energy ($m^3\,s^{-2}$)
F	force (kg $m^{-1}\,s^2$)
$f(\alpha)$	impingement angle function
g	gravity acceleration (m s^{-2})
$H(\upsilon)$	attenuation of turbulent kinetic energy due to droplets
$\langle j \rangle$	super facial velocity (m s^{-1})
k	turbulent kinetic energy ($m^2\,s^{-2}$)
l	macroscopic length scale of turbulence (m)
m	droplets mass (kg)
M	momentum loss or gain (kg m s^{-1})
p	pressure (Pa)
t	time (s)
Re	Reynolds number
R_υ	normalized relative velocity between two phases (m s^{-1})
R	erosion rate (kg $m^{-2}\,s^{-1}$)
r	radius (mm)
U	mean velocity (m s^{-1})
u_d	droplet velocity (m s^{-1})
v	velocity (m s^{-1})
V_d	droplet volume (m^3)
W	mass concentration of droplets
x	coordinate direction (m)
y	coordinate direction (m)
Greek	
α	volume fraction, droplet impingement angle
ε	dissipation of turbulent kinetic energy ($m^3\,s^{-2}$)
η	Kolmogorov microscale of turbulence (m)
μ	dynamic viscosity (kg $m^{-1}\,s^{-1}$)
υ	wavenumber (m^{-1})
ξ	Kolmogorov constant
ρ	density (kg m^{-3})
δt_d	time step (s)
Indices	
am	virtual mass force
c	carrier
d	droplets
dr	drag force
n	new values
o	old values
tp	two phases

may have strong impact on the turbulent flow, either enhancing or suppressing carrier turbulence. Experimental data show that in case of larger particles with high particle Reynolds number which is beyond the production of turbulence by the main flow, an additional production of turbulent kinetic energy due to vortex shedding by the particles. Conversely, turbulent kinetic energy is suppressed for small particles with lower particle Reynolds number due to the entrained particles in the oscillating motion of the fluid molecules, with dissipation of energy due to shear (Corrsin and Lumley, 1965; Pao, 1965). As discussed in the beginning for LDI phenomenon there is no open literature study due to the difficulties of experiments, so the numerical study is strongly demanded.

For the numerical simulation, in the past turbulence modification due to the presence of particles was made using an Eulerian approach by Durst et al. (1984) and Elgobashi (1984). On the other hand, most of the recent investigations follow the Lagrangian approach, where individual particle trajectories are computed

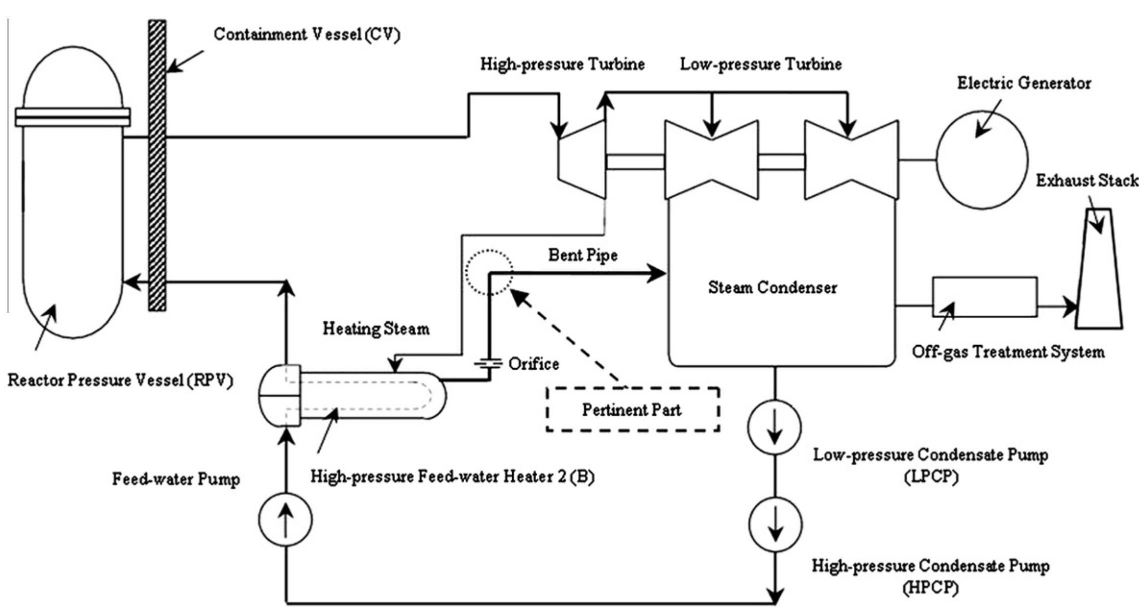

Fig. 1a. The system diagram of the components near the high pressure feed-water heater (JSME, 2007).