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STUDY OF FLUID-STRUCTURE INTERACTION IN LIQUID DROPLET IMPINGEMENT PHENOMENA

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This paper has as main objective modeling and simulation of fluid-structure interaction that occurs in LDI erosion. The fluid-solid interface pressures were determined and the variation of the plastic energy transferred from the droplet to solid with certain parameters of influence (angle and speed of impact) was studied. A new energetic approach was used to determine the erosion resistance of the materials considering the simulation results of the impact.

Keywords: LDI erosion, fluid-structure interaction, CFD modeling

1. Introduction

NPPs worldwide are showing continuous improvements in their performance and availability. This applies to overall plant safety as well. However, problems associated with materials (in more general terms, system, structure and component (SSC) degradation followed by spontaneous failure) have been observed [1]. In order to reduce the likelihood of repeated occurrence of failures, despite already well known and documented incidents, the combination of a wide spectrum of activities, ranging from the effective use of operational experiences, continued research into the mechanisms of material failure, transparency in sharing information, avoidance of complacency, and optimized knowledge management is needed.

Safety of the nuclear power plants depends, to an important degree, on the erosion and erosion-corrosion durability of the equipment and especially pipelines, which work in single-phase and double-phase flows of coolant [2]. LDI (Liquid Droplet Impingement) erosion represents a complex mechanism of material degradation due to the impact of liquid particles (droplets) contained into a continuous medium with high kinetic energy. There have been a lot of research activities in this area [3, 4] and the causes of damage occurrence are well established, the initiation and time evolution of the erosion and the parameters affecting the phenomena are known. But, there is no universal correlation that gives the damage rate for any material in any operating conditions.

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Until now, numerical simulations of the liquid particles impact have used one of the approaches [5, 6]: (1) fluid and inelastic material, in which one only simulates the liquid particle without considering the influence of solid deformation, (2) fluid and elastic material, in which the elastic material deformation is considered. The second method gives more realistic results and the maximum stresses in the material are deduced directly as a result of the simulation. In both cases for determination of the specific erosion rates is necessary a fatigue analysis.

The use of CFD (Computational Fluid Dynamics) and FSI (Fluid Structure Interaction) codes can offer new perspectives on the phenomena and can predict the behavior of materials under LDI conditions. Modeling and simulation of the impact could consider all the parameters involved in the process and the complex interaction between them. The main objectives of this paper were the numerical simulation of the interaction between fluid and solid considering the plastic deformation of the material and the use of plastic energy of deformation to predict the erosion rates for various input parameters.

2. The governing equations for fluid and solid domains

The impact velocity of the particles for this kind of phenomena is normally found to be in the range 50-1000 m/s and particle sizes ranging from 10 µm to several millimeters. With these data, we can determine the Reynolds criterion ($Re = (w \cdot d)/\nu$) and choose the appropriate fluid model to be used in simulations. Usually, Euler equations are used for modeling the fluid domain since viscosity influences on the particle dynamics are minimal. Also, the Weber criterion ($We = (\rho \cdot d \cdot w^2)/\sigma$) is used to consider the influence of surface tension on the formation of the lateral jets. In this study water particles with a diameter of 100 µm are used, the fluid is modeled as ideal and the influence of surface tension is neglected.

To study the propagation of pressure waves inside the droplet the liquid compressibility effects require to be considered. Equation of state (EOS) of water has the polynomial form given below:

$$p = A_1 u + A_2 u^2 + A_3 u^3 + (B_0 + B_1 u)\rho_{ref} E\,, \quad (1)$$

where $u=\rho/\rho_{ref}-1$, A_1, A_2, A_3, B_0, B_1 and ρ_{ref} are given in Table 1.

Table 1

Coefficients used in EOS for water

A_1 [Pa]	A_2 [Pa]	A_3 [Pa]	B_0	B_1	ρ_{ref} [kg/m^3]	E [J/kg]
2.2E9	9.5E9	1.4E10	0.28	0.28	1000	361.8

To obtain the plastic deformation inside the solid the plastic behavior must be considered. An elastic-viscoplastic material [7] with strain hardening is described by equations similar to those for a elastic-viscoplastic material with perfect plasticity. However, in this case the stress depends both on the plastic strain rate and on the plastic strain itself:

$$\varepsilon = \varepsilon_e = E^{-1}\sigma \text{, for } |\sigma| < \sigma_y, \tag{2}$$

$$\varepsilon = \varepsilon_e + \varepsilon_{vp} = E^{-1}\sigma + f(\sigma, \sigma_y, \varepsilon_{vp})\sigma \text{, for } |\sigma| > \sigma_y, \tag{3}$$

where $f(\sigma, \sigma_y, \varepsilon_{vp})$ is a yield function, σ is the Cauchy stress, ε_{vp} is the plastic strain.

In this paper the yield function is given by an empirical model, Johnson-Cook relation:

$$\sigma_y(\varepsilon_p, \dot{\varepsilon}_p, T) = [A + B\varepsilon_p{}^n][1 + C\ln(\dot{\varepsilon}_p{}^*)][1 - (T^*)^m], \tag{4}$$

where ε_p is the equivalent plastic strain, $\dot{\varepsilon}_p$ is the plastic strain-rate, and A, B, C, n, m are material constants.

The normalized strain-rate and temperature in Eq. (4) are defined as:

$$\dot{\varepsilon}_p{}^* = \dot{\varepsilon}_p / \dot{\varepsilon}_{p0} \text{, and } T^* = (T - T_0)/(T_m - T_0), \tag{5}$$

where $\dot{\varepsilon}_{p0}$ is the effective plastic strain-rate of the quasi-static test used to determine the yield and hardening parameters A , B and n. T_0 is a reference temperature, and T_m is a reference melt temperature.

3. Computational study of high-speed liquid droplet impact

To study the wave propagation inside a solid specimen considering the elasto-plastic behavior of the material the AutoDyn code [8] was employed. The code permits the automatic calculation of the plastic work performed in the material if a proper strength model is used. The material simulated was Steel 4340. The yield stress for Steel 4340 is given by Eq. 6:

$$\sigma_y = [7.92e5 + 5.1e5 \cdot \varepsilon_p{}^{0.26}][1 + 0.014\ln(\dot{\varepsilon}_p{}^*)], \tag{6}$$

AudoDyn code has an explicit solver; the transient simulation time step is automatically controlled to meet the criterion of stability of solutions. Mesh grid cell size was chosen equal to 0.25 µm (D_{drop}/400).

For this case the droplet radius was chosen R_{drop} = 50 µm, the impact velocity V = 500 m/s and the impact angle β = 90^0.

From previous studies of the impact at 90^0 was noted that the maximum pressure obtained in liquid-solid interface occurs just before the time of formation of lateral jets. The maximum value of this pressure is typically in the range (2÷3)p_{wh}, where p_{wh} represents the water hammer pressure obtained using the particle impact velocity.

The pressure at the interface at different moments of time on the liquid side is presented in Fig. 1. From this chart we can notice that the maximum pressure is almost p_{max} = 2e9 Pa obtained at ratio r/R_{drop} = 0.3. For this case the droplet impact velocity is 500 m/s, the density of the fluid is 1000 kg/m^3 and the sound velocity in fluid is almost 1500 m/s. With this values the water-hammer pressure is p_{wh} = 7.5e8 Pa.

The ratio between maximum pressure and the water-hammer pressure is almost 2.6.

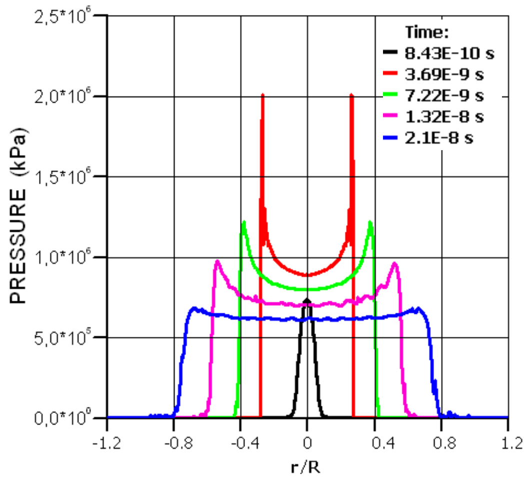

Fig. 1. Pressure at the liquid-solid interface

At r = 0 µm the maximum pressure obtained is close to water-hammer pressure and maintains a constant value in time. After the jetting, the pressure at the surface decreases and tends to the water-hammer pressure. The pressure at the interface decreases immediately after the jets starts at t = 3.7e-9 s. We can observe the large gradients of the pressure near the contact front.

The pressure near the front will increase as long as the speed of the front in horizontal direction is greater than the speed of sound in liquid. When the two velocities becomes equal pressure wave will pass the front line and the lateral jets starts which will cause a pressure decrease. The area with high pressure will increase and move in the center at the interface water-solid.

The deceleration of the fluid starts immediately after the moment of impact and the velocity of the fluid inside the droplet is reduced as the pressure waves propagates longitudinally and transversally.

Because the fluid is considered inviscid and no friction is assumed between fluid and solid, the velocity of the lateral jets remains almost constant after the jetting starts. The maximum velocity is 2400 m/s which represent almost five times the impact velocity. This high value of the velocity of the jets proves that the hypothesis of inviscid fluid was right.

4. Determination of erosion ratios and the dependence on input parameters

An energetic method that takes into account the plastic deformations and the plastic work performed upon the solid can be used to calculate the erosion ratios. In this approach one need the static mechanical properties and the dynamic curves of the material (the strain and strain rate hardening). These dynamic characteristics are already known for some material or can be deduced theoretically for others. The main scope of this paper is to introduce this energetic method and to compare the obtained results with experimental data.

The erosion ratio is defined as the mass of material removed in a certain period of time per total mass of liquid impinging the wall.

Using the simulation of one droplet impact on a material assumed to have an elastic-plastic behavior one can determine the plastic energy transferred from the droplet to the solid. This energy represents only a small fraction from the total kinetic energy of the droplet, thus being very difficult to measure this quantity experimentally. But the fluid-structure interaction codes (e.g. Ansys AutoDyn) permits to model and simulate such a small scale phenomena (μm scale) with time scale of order of nanoseconds.

Assuming that the mean energy absorbed by a unit volume of ductile material to fracture is equal to:

$$E_{fracture} = \varepsilon_{fract} \cdot \sigma_{fract} \, , \tag{7}$$

and the plastic energy transferred to the material is determined from the simulation and is noted as PlW, the erosion ratio can be calculated as:

$$ER = (PlW \cdot \rho_{material})/(m_{drop} \cdot E_{fracture}) \, , \tag{8}$$

where: $\rho_{material}$ is the density of solid and m_{drop} is the particle mass.

A set of simulations was performed for a droplet radius R_{drop} = 50 μm, the solid material being Steel 4340. The first parameter varied was impact velocity keeping the impact angle at $\beta = 90^0$. The trend obtained is presented in Fig. 2. The law of variation of the erosion ratio with the impact velocity respects a power law having one of the general forms:

$$ER = A \cdot V^n \quad \text{or} \quad ER = B \cdot (V - V_{treshold})^m \, , \tag{9}$$

These variations are obtained from experimental results and are given in literature for many materials. The coefficients *A*, *B* and the power coefficients *m*, *n* are valid only for a specified range of impact velocity.

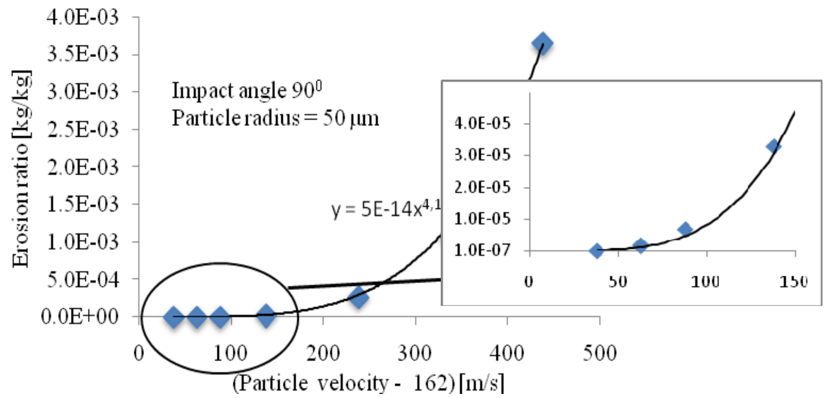

Fig. 2. Erosion ratio variation with impact velocity, dry surface

From the simulation results we can notice that the variation with impact velocity for Steel 4340 is a power law with the coefficients B = 5e-14, n = 4.1204 and $V_{treshold}$ = 162 m/s. In general the power coefficient n varies between 4 and 7 depending on the material and threshold velocity.

In Fig. 3 the variation of the erosion ratio with the impact angle is presented for impact velocity V = 500 m/s. The best fit is a polynomial function of 3rd order.

Using the correlation obtained from Fig. 2 one can calculate the damage ratio using the normal component of the velocity for oblique impact. These values are plotted in the chart (Fig. 3) as red dots. As we can observe these are in good agreement with those obtained from oblique simulations. This dependence of the erosion rate only on the normal velocity of the impact can be observed for the experimental results. This proves that the tangential velocity has no major effect on the damage produced upon the material.

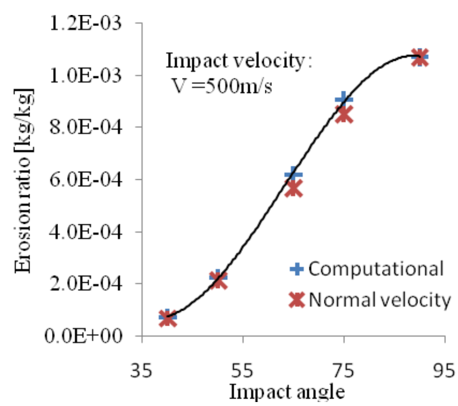

Fig. 3. Erosion ratio variation with impact angle, impact velocity V = 500 m/s

5. Conclusions

The main purpose of this study was to introduce a new method to determine the erosion resistance of materials subjected to LDI damage. The use of computational analysis can offer a new perspective on the phenomena and the characteristic curves can be easily obtained for a specific set of conditions.

It was considered that the strain and strain rate hardening stop the plastic deformations of the material. But, the high value of the maximum load and the small region (few microns) on which the pressure is applied produces plastic work inside the solid. This energy can be used further to calculate the erosion damage. This method is valid only for the ductile materials for which the fracture occurs because of the incremental plastic deformations. For brittle fracture the material presents a more complicated pattern of damage; the surface is cracked and when cracks are united in subsurface the material is removed.

As a simulation input one must known the dynamic mechanical properties of the material. The plastic behavior (in this study the Johnson Cook flow curve) is necessary for an accurate prediction of the damage. In the absence of this data, a fatigue analysis can be performed using the maximum stresses inside the solid obtained as a result of a fluid-structure interaction simulation using an elastic behavior of the solid.

The simulation of 90^0 degrees impact has shown that the maximum pressure obtained at the interface is almost 2.6 - 3 times higher than the water hammer pressure and is obtained right before the lateral jets are formed. This maximum pressure is responsible for the material removal. In the case of oblique impact, the maximum pressure is reduced and the pattern of the plastic work inside the solid is different than in the case of normal impact, but the same amount of energy is transferred as 90^0 degrees impact using only the normal component of the velocity. This proves that the tangential velocity has no influence on the damage because the liquid droplet is easy deformed by the solid surface. The tangential velocity could became important in the case of high roughness of the surface, but only if the height of the roughness is higher than the liquid film formed on the surface.

From the computational curves, the LDI erosion ratio respects the power law, which is in accordance with the experimental observations.

The simulation of the fluid-structure interaction represents the most complicated step in the process of evaluation of the material degradation.

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