Two-Dimensional, Two-Phase Jet Loading on Containment Structures During Blowdown

S. Mohammadian, L. Slegers

Kraftwerk Union AG, Abteilung R 612, Berliner Str. 295-299, D-6050 Offenbach/Main, Germany

Abstract

Pressure profiles of impinging jets are calculated using the computer code BEACON/MOD3. The code is used in post-as well as precalculations of experiments to demonstrate its applicability in 2-phase jet load calculation. Solutions are obtained for large scale HDR experiments:

HDR	V 67.1	Steam-water flow
HDR	V 67.2	Subcooled water flow
HDR	V 42	Steam flow

Comparisons between measurements and predictions show that the code predicts pressure profiles within 15% accuracy.

1. Introduction

As part of the safety design of the containment for light water reactors, jet forces resulting from the postulated rupture of high pressure piping are accounted for in the design of internal structures. Jet forces resulting from liquid as well as steam carrying piping are considered. The forces are determined on a calculated basis allowing for a flow divergence between the point of discharge and the point of impact. The model for determining flow divergence is based on empirical relations for nonconfined jets and specified in several standards /1, 2/. Based on such models the width and distribution of a pressure profile on the impacted wall is determined.

During the last few years numerical solution methods for two-dimensional two-phase flow solutions have been developed that allow a complete solution for the two-phase jet impinging on a flat plate.

The computer code BEACON/MOD3 /3/ employs such a method. Calculations with this code for several large scale jet flow experiments on instrumented flat plates are shown together with the experimental results of the HDR * testprogram as a comparison with existing practice the specified procedure of determining jet divergence in current design procedures is also shown in the results.

2. Description of the code and its application

BEACON is a best-estimate, advanced containment code designed to predict conditions within a nuclear reactor containment system during a postulated loss-of-coolant accident. The current version of the code, BEACON/MOD3, incorporating all of the developments to date, is suitable for analysis of short-term transient behavior of dry containment systems including heat conduction to surrounding walls.

The BEACON numerical technique is based on the K-FIX /4/ method. Each phase (gas or liquid) is described by its own density, velocity, and temperature as determined by separate sets of mass, momentum, and energy equations. The two phases are coupled by exchange parameters which model the exchange of mass, momentum, and energy between the two phases. The two sets of field equations are solved with an Eulerian finite difference technique which is an extension of the implicit multifield (IMF) method developed in the K-FIX code. In the K-FIX numerical technique the phase transitions and interphasic heat transfer are treated implicitly in the pressure iteration. The implicit solution is accomplished iteratively without linearization and allows both phases to be compressible. The coupling between the two phases can be very loose as occurs with separated flow or very tight as with finely dispersed flow. The K-FIX numerical technique also allows computations for single-phase gas flow

* Heißdampfreaktor (Superheat Reactor) Kahl, FRG

without special treatment. The version of K-FIX used in BEACON can handle air as a second gas component.

The code allows joining 2-dimensional mesh regions to model complicated flow fields. The boundary condition can be modeled with one of the following options: No-slip rigid wall, Free slip rigid wall, prescribed inflow, continuative out flow and constant pressure.

The jet force experiments were modeled in axisymmetric coordinates with the computational region extending from the exit plane of the discharge pipe to the impacted plate employing a variable mesh spacing. An example of such a nodalization is shown in Fig. 1 using a rigid no slip boundary on the plate and prescribed inflow corresponding to the discharge conditions at the pipe exit. The initial condition of the solution prescribes atmospheric condition at rest within the entire region. Starting with this initial condition computations are performed until a nearly steady-state solution in the flow region is obtained.

For improved stability in the numerical solution extended mesh regions as shown in Fig. 2 and Fig. 3 were included with boundary conditions as shown. This method of modeling not only assured stability of the solution for all expansion lengths (distance between point of discharge and point impingement of the jet) but also improved the accuracy of the velocity prediction at the edge of the plate.

The two-phase model in the code employs the "Best estimate" option of BEACON/MOD3 for setting the transport parameters between the phases. The state relation is based on an option treating the gas phase as ideal gas and the liquid phase as incompressible.

3. Analyses and comparison with experimental results

Extensive analyses were performed with BEACON/MOD3 for the impinging jet problem. Of these three solutions for the following large scale HDR experiments are shown

- HDR V 67.1 Steam-water mixture flow
- HDR V 67.2 Subcooled water flow
- HDR V 42 Steam flow

for which the test parameters are shown in Table 1. The first two solutions were obtained as a post analysis; the solution for V 42 is precalculation performed before the experiment was run in 9/1982.

3.1 Steam-water mixture flow

The calculated results for pressure and velocity along the axis of rotation are shown in Fig. 4. Included in the figure is the exit geometry of the discharge pipe showing a stepwise diameter increase 450 mm forward of the exit plane. The inflow boundary condition was placed at the transition from 350 mm to 450 mm diameter imposing the experimentally determined values for nearly steady state flow conditions at time = t_s as shown in Table I at the pipe exit location. The flow is prescribed by velocity, pressure, temperature and void fraction.

The solution shows a nearly constant pressure and velocity as long as the jet is confined in the pipe extension. Upon discharge from the pipe the pressure expands to atmospheric conditions before recovering to 3.2 bar at the stagnation point. The highest velocity along the centerline is 170 m/s.

Figure 5 shows the pressure distribution on the plate at a problem time of 24 ms at which time the massflow at the edge of the plate approaches the massflow from the jet indicating a nearly steady state solution. The analysis underpredicts the data in the center of the plate. The analytic pressure profile is flatter than the pressure measurement resulting in a cross over away from the stagnation point and slight overprediction at the edge of the plate where the static pressure approaches atmospheric conditions.

The Force on the plate is determined by means of a pressure area integration and a direct force measurement. The latter agrees more closely to the calculated force on the plate ($F_{\text{measured}} = 360 \text{ kN}$, $F_{\text{BEACON}} = 389 \text{ kN}$) pointing at possible inaccuracy in pressure measurements at the stagnation point.

3.2 Subcooled water flow

For the same geometry as above and the measured inflow condition as shown in Table I an analysis was performed for a cold water jet. The static pressure of 1 bar at the Ø 350 exit location decreases to the saturation pressure of about 0.1 bar in the pipe extension showing an ejector effect in this geometry. Outside of the pipe the results in Fig. 6 show a nearly constant velocity of 55 m/s and pressure of 1 bar along the centerline increasing to 16 bar at the stagnation point. The much more peaked pressure profile calculated for the cold water jet is shown in Fig. 7 together with the measurements and their estimated error band. A pressure measurement at the stagnation point is not available. The calculated stagnation pressure of 16 bar is confirmed as the stagnation pressure for the flow at 55 m/s.

Due to insufficient pressure measurements to resolve a reliable pressure profile a measured force by pressure integration can not be made.

3.3 Steam flow

The analysis for test V 42 were performed as precalculations before the test was run. Fig. 8 shows the pressure and velocity along the centerline. The static pressure drops off to atmospheric values along the centerline before reaching a stagnation pressure of 7 bar. This shows that at a plate distance of 2 diameters the steam jet fully expands before the static pressure is effected by the vicinity of the plate. In the fully expanded region a velocity of 900 m/s is calculated equivalent to a Mach number $M = 2$ which is in agreement with the one dimensional gas dynamics prediction for the applicable upstream pressure ratio.

The pressure profile in Fig. 9 shows good agreement with the few reliable measurements that were obtained. The analysis shows that the static pressure at the edge of the plate is about 1/2 bar above atmospheric conditions indicating that the expanding steam jet is not fully deflected by the plate diameter of 2.25 m.

4. Comparison with design practice

Present design requirement for specifying jet force distribution in containment have been evaluated for these experiments. The procedure in /1/ allows for a 10° half angle originating from the inside diameter of the discharge pipe, with an allowance for a larger expansion in a downstream range of 5 pipe diameters for steam and saturated water-steam mixture when such a procedure is justified. The ANSI/ANS 58.2 /2/ includes a procedure to determine an effective expansion larger than 10° . However for subcooled water flow no expansion is allowed. The pressure in each case is specified as a constant value over the impacted area. To compare the design procedure used in licencing with the analysis presented here, the jet force envelope based on plant design procedures is included as a dashed line in the figures 5, 7 and 9.

5. Conclusion

With the described approach to modeling the jet force problem in 2-phase flow suitable solution for the jet expansion and the pressure profile on the plate can be obtained. The present results for single phase jets (steam and cold water) show good agreement when compared with pressure measurements. Comparison between calculation and pressure measurement for two phase jet is less satisfactory although better agreement is achieved with the force measurement.

The current best estimate option in the code couples the phases in such a manner that in the present scale of problems no noticeable slip is shown

between the phases for mixture flow.

For wall distances representatives of plant condition (distances greater than 2 diameters) these results show the jet nearly fully expanded before a rise in static pressure due to the vicinity of wall takes place.

The current methods of calculating jet expansion show substantial conservatism as shown by the pressure envelopes required by safety design in comparison with the present analysis and experiments.

References

- /1/ American Nuclear Society
ANSI/ANS -58.2- 1980.
- /2/ USNRC Standard Review Plan
NUREG - 75/087 Kap. 3.6.2 September 75.
- /3/ BEACON/MOD3, A computer program for thermalhydraulic analysis of
nuclear reactor containments
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- /4/ K-FIX, A computer program for transient,
two-dimensional, two-fluid flow
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Table I

Measured steady state flow variables at time t_{st} in experiment
and input values for the calculations ($\dot{m}$ - massflow, P - pressure,
T - temperature, W - velocity, Θ - voidfraction,
all at point of discharge)

Experiment	Measured values				Values used for calculations				
	t_{st}	$\dot{m}$	P	T	$\dot{m}$	P	T	W	Θ
	sec	kg/sec	bar	°C	kg/sec	bar	°C	m/s	
V 67.1	0.3	4500	28	220	4500	28	220	55.64	0
V 67.2	0.3	5200	1	50	5200	1	50	54.7	0
V 42	0.1	1535	36	240	1534	38.2	248	439	0.997

Figure 1: Simple method of noding the jet experiments

Figure 2: Methods of extended noding for jet impingement analysis

Figure 3: Nodalisation for Analysis of the V 67.1 and V67.2 jet experiments

Figure 4: Calculated pressure and velocity distributions at the jet centerline of the V 67.1 two phase jet experiment

Figure 5: Pressure distribution of the V 67.1 two phase jet experiment

Figure 6: Calculated pressure and velocity at the Jet centerline of the V 67.2 cold water jet experiment

Figure 7: Pressure distribution of the V 67.2 cold water jet experiment

Figure 8: Calculated pressure and velocity along the jet centerline of the V 42 jet experiment

Figure 9: Pressure distribution of the V 42 steam jet experiment