Purdue University
School of Nuclear Engineering

NUCL 355 - Nuclear Thermal-Hydraulics Laboratory

Experiment 13: Blowdown Experiment

Objectives: Study the phenomena of two -phase blowdown in a pipe system and demonstrate the essential features of the Loss of Coolant Accident (LOCA). Specifically when a LOCA occurs:

1. Observe various phenomena during the vessel depressurization.
2. Measure vessel depressurization and vessel water level and relate to critical flow model.

Apparatus and instruments: The schematic of the experiment setup is shown in Figure 1. It consists basically of a pressure vessel, horizontal test pipe, a dry well and a wet well.
A water valve enables transfer of city water to the pressure vessel. The pressure vessel is heated with immersion electrical heaters. The power sent through the heaters can be controlled with a microprocessor. The pressure vessel is instrumented with a J type thermocouple embedded on the vessel wall. The thermocouple can be used to get the desired initial water temperature (and so the desired saturation pressure) in the pressure vessel.
The experiment is instrumented with pressure transducers and pressure gauges. A differential pressure transducer is calibrated to give instantaneous liquid level in the pressure vessel. The positions of the pressure taps for the level pressure gauge are shown in Figure 2.
The exit of the test section comprises of an orifice plate and expansion zone which connects to drywell. The drywell has glass windows for flow visualization. The pressure vessel ID is 4.026 inch and the orifice size is 0.255 inch. The pipe connecting the vessel to the nozzle is of 0.5 inch ID. The water heated in the pressure vessel is blown down opening the valve between the nozzle and the drywell. The saturated water flashes as it travels through nozzle tube and finally expands in to steam in the drywell. The steam exiting from drywell is condensed in the wetwell. The data acquisition system enables to measure the output from the pressure transducers.

Procedure:

1. Before starting the experiment, be sure that all apparatus are properly connected, all valves are in shut-off position and the power controller is in the off position;
2. Power the pressure transducers and the data acquisition system.
3. Open the air relief valve of the vessel and the top blowdown valve;

4. Fill the pressure vessel with water from the wet well;
5. Stop the water after it starts to drain from the blowdown line and close the air relief valve.
6. Set the thermostat level at 171^0C (Psat=100 psi);
7. Monitor the vessel pressure and temperature.
8. When the vessel pressure is about 5 psi bleed steam from vessel from air relief valve to purge any air from pressure vessel.
9. When vessel pressure reaches 100 psi, the system is ready to run;
10. Shut off the power controller;
11. Open quickly the blowdown valve and start acquiring data with the data acquisition system.
12. Make visual observation of the flow in the drywell and wetwell.
13. Once the pressure vessel vapor is depleted, valve #2 is closed and valve #4 is open, allowing reflood of the dry well;
14. The condensed water is then allowed to drain back into the wet well, and the experiment is concluded.

Precautions:

1. Maximum pressure for the pressure vessel should not exceed 120 psi.
2. Before starting the blowdown, after the water is heated to required saturated temperature, make sure to shutoff the supply to immersion heaters.
3. Do not touch piping or vessels during the run. They are HOT!

Write up:

In your report you should describe carefully those physical mechanisms that are significant during a LOCA:

1. Plot transient profiles for water level and vessel pressure and discuss the phenomena.
2. Compare the experimental flow rates 40 seconds into the experiment with computational results using the two phase choked flow model available. Please sue the attached paper -Henry Fauske model for critical flow calculation.

References:

1. Wallis, G.B., One Dimensional Two Phase Flow, McGraw Hill Com., 1969.
2. Fauske, H.K., Two -phase Critical Flow, 7th National Heat Transfer Conf., Cleveland, Ohio, 1964.
3. Lahey, R.T. and Moody, F.J., The Thermal Hydraulics of a Bliling Water Nuclear Reactor, American Nuclear Society, 977.
4. Moody, F.J., Maximum Two- phase Blowdown From Pipes, ASME, Journal of Heat Transfer, 285-295, 1996.

Experimental Apparatus

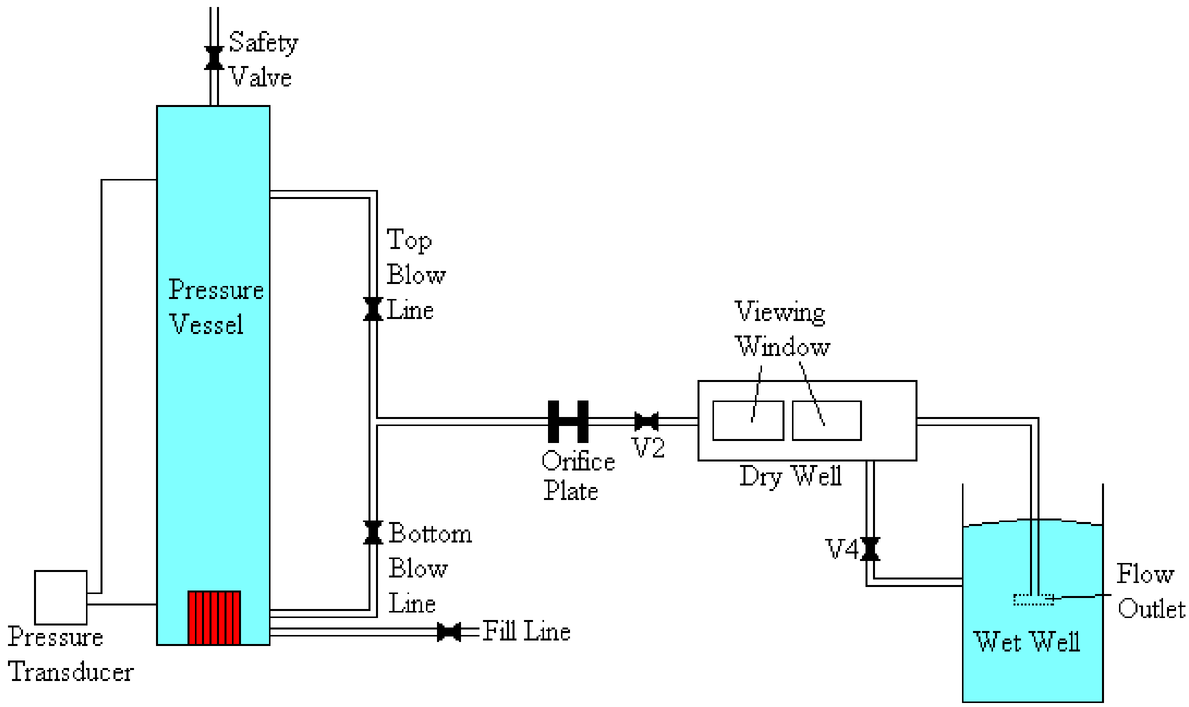

Figure1: Blowdown experimental test facility

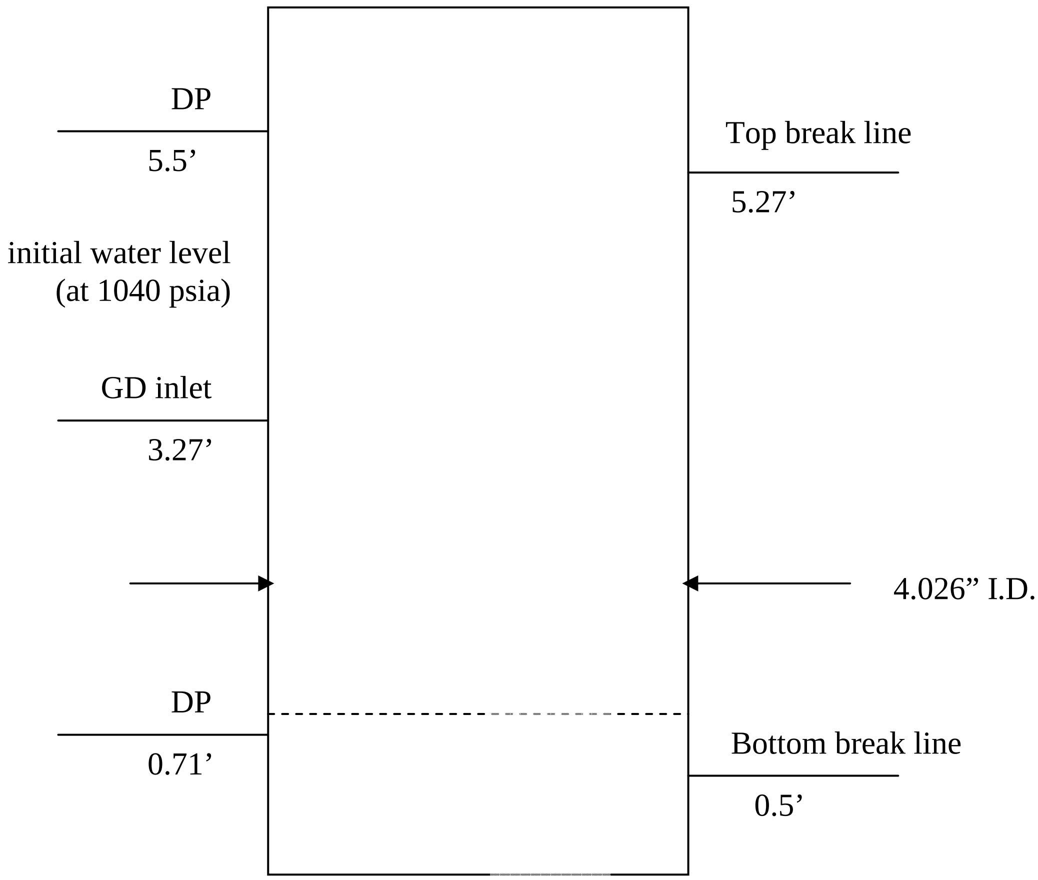

Figure 2: RPV showing the elevation of penetrations above the bottom of the RPV in feet

SIZING RUPTURE DISKS (RDs) FOR TWO-PHASE FLOW

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SUMMARY

An easy and accurate method for estimating two-phase flow through RDs is outlined. Given information about stagnation conditions the model can handle gas-liquid, vapor-liquid and hybrid flows including subcooled flashing flows. Examples are provided illustrating sizing of RDs for gas-liquid, vapor-liquid, hybrid and flashing flows. The examples illustrate the importance of considering two-phase flows when sizing rupture disks.

INTRODUCTION

RDs are extensively used for overpressure protection in the chemical process industries and sizing methods for all liquid and all gas flows are well established and easy to use (see Fike Metal Products catalog). In comparison, two-phase flow methods proposed over the years have been far more complex and difficult to use than the single-phase flow methods. Here we introduce an equally easy to use two-phase flow method with accuracy equal to or better than that provided by the more complex models (Fauske, 1998).

The RD size is obtained by assuring a balance between the required venting rate, W (kg/s) and the discharge rate

$$W = K_d \, A \, G \tag{1}$$

where K_d (0.62) is the rupture disk flow coefficient given in the ASME Boiler and Pressure Vessel Code (1983), A (m^2) is the vent area, and G (kg/m^2-s) is the two-phase mass flux given by

$$G = \left[\frac{1-x_o}{G^2_{x_o=0}} + \frac{x_o}{G^2_{x_o=1.0}} \right]^{-1/2} \tag{2}$$

where x_o is the stagnation gas and/or vapor quality.

GAS-LIQUID FLOWS

For two-compartment two-phase flows such as air-water flows, $G_{x_o=0}$ is determined

$$G_{x_o} = \sqrt{2\left(P_o - P_b\right)\rho_{\ell,o}} \tag{3}$$

where P_o (Pa) is the stagnation pressure, P_b (Pa) is the back pressure, and $\rho_{\ell,o}$ (kg/m^3) is the liquid density. For critical flows $G_{x_o=1.0}$ is given by

$$G_{x_o=1.0} = P_o \left(\frac{M_w}{R\,T_o} \right)^{1/2} \left[k \left(\frac{2}{k+1} \right)^{(k+1)/(k-1)} \right]^{1/2} \tag{4}$$

and for subcritical flows by

$$G_{x_o=1.0} = P_o \left(\frac{M_w}{R\,T_o} \right)^{1/2} \left\{ \left(\frac{2\,k}{k-1} \right) \left[\left(\frac{P_b}{P_o} \right)^{2/k} - \left(\frac{P_b}{P_o} \right)^{(k+1)/k} \right] \right\}^{1/2} \tag{5}$$

where M_w is the molecular weight, R (8314 Pa-m^3/K-kg-mole) is the gas constant, and k is the isentropic coefficient (see Table 3, Fike Metal Products Catalog, for values of k).

VAPOR-LIQUID FLOWS

For one-component two-phase flows, such as steam-water flows, $G_{x_o=0}$ can be estimated from

$$G_{x_o=0} = \rho_{v,o}\,\lambda_o \left(T_o\;c_o\right)^{-1/2} \tag{6}$$

where $\rho_{v,o}$ (kg/m^3) is the stagnation vapor density, λ_o (J/kg) is the latent heat of vaporization, T_o (K) is the stagnation temperature and c_o (J/kg-K) is the liquid specific heat. Similar to two-component two-phase flows $G_{x_o=1.0}$ is given either by Equation (4) or Equation (5).

HYBRID GAS-VAPOR-LIQUID FLOWS

For hybrid two-phase flows such as air-steam-water flows $G_{x_o=0}$ is determined from

$$G_{x_o=0} = \left[2\ P_{g,o}\ \rho_{\ell,o} + \lambda_o^2\ \rho_v^2 / T_o\ c_o\right]^{1/2} \qquad (7)$$

where $P_{g,o}$ (Pa) is the stagnation gas partial pressure and $G_{x_o=1.0}$ is again given by either Equation 4 or Equation 5 with the molecular weight M_w given by

$$M_w = M_{w,g}\left(P_{g,o}/P_o\right) + M_{w,v}\left(P_{v,o}/P_o\right) \qquad (8)$$

where $P_{v,o}$ (Pa) is the vapor pressure corresponding to the stagnation temperature T_o. The value of the isentropic coefficient k can be estimated in a similar manner.

ALL LIQUID FLASHING FLOWS

For all liquid initial conditions, Equation 2 reduces to $G = G_{x_o=0}$. In case of saturated inlet or stagnation conditions, G is determined from

$$G = \rho_{v,o}\ \lambda\left(T_o\ c_o\right)^{-1/2} \qquad (9)$$

and for subcooled inlet conditions the expression is the same as that for hybrid vapor-gas-liquid flows with $x_o = 0$

$$G = \left[2\ P_{g,o}\ \rho_{\ell,o} + \lambda_{v,o}^2 / T_o\ c_o\right]^{1/2} \qquad (10)$$

EXAMPLE 1 - SIZING FOR GAS-LIQUID FLOWS

What size rupture disk is required to relieve an air-water mixture under the following conditions:

W = 50 kg/s, x_o = 0.01, $P_o = 7 \bullet 10^5$ Pa,
$P_b = 10^5$ Pa, T_o = 300 K, and $\rho_{\ell,o} = 10^3$ kg/m^3.

$$G_{x_o=0} = \sqrt{2\left(7 \bullet 10^5\right)1000} = 3.46 \bullet 10^4\ kg/m^2 - s$$

+

$$G_{x_o=1.0} = 7 \bullet 10^5\left(\frac{29}{8314 \bullet 300}\right)^{1/2}\left[1.4\left(\frac{2}{1.4+1}\right)^{\frac{(1.4+1)}{(1.4-1)}}\right]^{1/2}$$
$$= 1.63 \bullet 10^3\ kg/m^2 - s$$

$$G = \left[\frac{0.99}{\left(3.46 \bullet 10^4\right)^2} + \frac{0.01}{\left(1.63 \bullet 10^3\right)^2}\right]^{-1/2}$$
$$= 1.48 \bullet 10^4\ kg/m^2 - s$$

$$A = 50/\left(1.48 \bullet 10^4 \bullet 0.62\right)$$
$$= 5.44 \bullet 10^{-3} \quad or \quad 8.44\ in^2$$

Answer: 4 inch diameter rupture disk.

What size rupture disk is required to relieve only the gas portion of the above air-water mixture, all other conditions remaining the same.

$$A = \frac{W\ x_o}{K_d\ G_{x_o=1.0}} = \frac{50 \bullet 0.01}{0.62 \bullet 1.63 \bullet 10^3}$$
$$= 4.95 \bullet 10^{-4}\ m^2 \quad or \quad 0.77\ in^2$$

Answer: 1 inch diameter rupture disk, i.e., in case of no liquid entrainment the required rupture disk size is much smaller.

EXAMPLE 2 - SIZING FOR VAPOR-LIQUID FLOWS

What size rupture disk is required to relieve a vapor-liquid ethylene mixture under the following conditions:

W = 300 kg/s, x_o = 0.01, $P_o = 2 \bullet 10^6$ Pa,
$P_b = 10^5$ Pa, T_o = 245 K.
Other physical properties: $\rho_{v,o}$ = 38.5 kg/m^3,
$\lambda_o = 3.2 \bullet 10^5$ J/kg, c_o = 3050 J/kg-K, M_w = 28,
and k= 1.26.

$$G_{x_o=0} = 38.5 \bullet 3.2 \bullet 10^5(245 \bullet 3050)^{-1/2}$$
$$= 1.43 \bullet 10^4\ kg/m^2 - s$$

+ Critical flow condition is used: $P_b/P_o = 0.143 <$ $P_c/P_o = \left(\frac{2}{K+1}\right)^{k/(k-1)}$ = 0.53, where P_c is the critical pressure.

$$G_{x_o=1.0} = 2 \bullet 10^6 \left(\frac{28}{8314 \bullet 245} \right)^{1/2} \left[1.26 \left(\frac{2}{1.26+1} \right)^{\frac{(1.26+1)}{(1.26-1)}} \right]^{1/2}$$

$$= 4.89 \bullet 10^3 \ kg/m^2 - s$$

$$G = \left[\frac{0.99}{\left(1.43 \bullet 10^4\right)^2} + \frac{0.01}{\left(4.89 \bullet 10^3\right)^2} \right]^{-1/2}$$

$$= 1.38 \bullet 10^4 \ kg/m^2 - s$$

$$A = 300/(1.38 \bullet 10^4 \bullet 0.62)$$

$$= 3.51 \bullet 10^{-2} \ m^2 \quad or \quad 54.4 \ in^2$$

Answer: 10 inch diameter rupture disk.

What size rupture disk is required to relieve only the vapor portion of the above ethylene mixture, all other conditions remaining the same

$$A = (300 \bullet 0.01)(4.89 \bullet 10^3 \bullet 0.62)$$

$$= 9.90 \bullet 10^{-4} \ m^2 \quad or \quad 1.53 \ in^2$$

Answer: 1-1/2 inch diameter rupture disk, i.e., in case of no liquid entrainment the required rupture disk is much smaller.

EXAMPLE 3 - SIZING FOR GAS-VAPOR-LIQUID HYBRID FLOWS

What size rupture disk is required to relieve an air-steam-water mixture under the following conditions:

W = 100 kg/s, x_o = 0.01, $P_o = 10^6$ Pa, T = 443 K,
$P_b = 10^5$ Pa.
Other physical properties: $P_{g,o} = 2.08 \bullet 10^5$ Pa,
$\rho_{\ell,o} = 8.97 \bullet 10^2$ kg/m^3, $\rho_{v,o}$ = 4.12 Kg/m^3,
$\lambda_o = 2.05 \bullet 10^6$ J/kg-K, and c_o = 4366 J/kg-K.

$$G_{x_o=0} = \left[2 \bullet 2.08 \bullet 8.97 \bullet 10^2 + \frac{\left(2.05 \bullet 10^6\right)^2 (4.12)^2}{(443)(4366)} \right]^{1/2}$$

$$= 2.2 \bullet 10^4 \ kg/m^2 - s$$

$$M_w = 29\left(2.08 \bullet 10^5/10^6\right) + 18\left(7.92 \bullet 10^5/10^6\right)$$

$$= 20.29$$

$$k = 1.4\left(2.08 \bullet 10^5/10^6\right) + 1.324\left(7.92 \bullet 10^5/10^6\right)$$

$$= 1.34$$

$$G_{x_o=1.0} = 10^6 \left[(20.29/(8314)(443)\right]^{1/2} \left[1.34 \left(\frac{2}{1.34+1} \right)^{\frac{(1.34+1)}{(1.34-1)}} \right]^{1/2}$$

$$= 1.58 \bullet 10^3 \ kg/m^2 - s$$

$$G = \left[\frac{0.99}{\left(2.02 \bullet 10^4\right)^2} + \frac{0.01}{\left(1.58 \bullet 10^3\right)^2} \right]^{-1/2}$$

$$= 1.25 \bullet 10^4 \ kg/m^2 - s$$

$$A = 100/(1.25 \bullet 10^4 \bullet 0.62)$$

$$= 1.29 \bullet 10^{-2} \ m^2 \quad or \quad 20.3 \ in^2$$

Answer: 6 inch diameter rupture disk.

What size rupture disk is required to relieve the above mixture in the absence of air, i.e., P_o is reduced to $P_{v,o} = 7.92 \bullet 10^5$ Pa with all other conditions remaining the same.

$$G_{x_o=0} = 4.12 \bullet 2.05 \bullet 10^6 \ (433 \bullet 4366)^{-1/2}$$

$$= 6.07 \bullet 10^3 \ kg/m^2 - s$$

$$G_{x_o=1.0} = 7.92 \bullet 10^5 \left(\frac{18}{8314 \bullet 443} \right)^{1/2} \left[1.324 \left(\frac{2}{1.324+1} \right)^{\frac{(1.324+1)}{(1.324-1)}} \right]^{1/2}$$

$$= 1.18 \bullet 10^3 \ kg/m^2 - s$$

$$G = \left[\frac{0.99}{\left(6.07 \bullet 10^3\right)^2} + \frac{0.01}{\left(1.18 \bullet 10^3\right)^2} \right]^{-1/2}$$

$$= 5.39 \bullet 10^3 \ kg/m^2 - s$$

$$A = 100/\left(5.39 \bullet 10^3 \bullet 0.62\right)$$

$$= 2.99 \bullet 10^{-2} \ m^2 \quad or \quad 46.35 \ in^2$$

Answer: 8 inch diameter rupture disk, i.e., in absence of air the required rupture disk diameter is significantly increased.

EXAMPLE 4 - SIZING FOR SUBCOOLED FLASHING FLOWS

What size rupture disk is required to relieve subcooled flashing water under the following conditions:

W = 100 kg/s, $P_o = 10^6$ Pa, T_o = 443 K,

$P_b = 10^5$ Pa.
Other physical properties: $P_{v,o} = 7.92 \bullet 10^5$ Pa, $P_{g,o} = 2.08 \bullet 10^5$ Pa, $\rho_{\ell,o} = 8.97 \bullet 10^2$ kg/m^3, $\rho_{v,o} = 4.12$ kg/m^3, $\lambda_o = 2.05 \bullet 10^6$ J/kg-K, and $c_o = 4366$ J/kg-K.

$$G = \left[2 \bullet 2.08 \bullet 10^5 \bullet 8.97 \bullet 10^2 + \frac{\left(2.05 \bullet 10^6\right)^2 \left(4.12\right)^2}{\left(433\right)\left(4366\right)} \right]^{1/2}$$

$$= 2.02 \bullet 10^4 \; kg/m^2 - s$$

$$A = 100/(2.02 \bullet 10^4 \bullet 0.62)$$
$$= 7.98 \bullet 10^{-3} \; m^2 \quad or \quad 12.37 \; in^2$$

Answer: 4 inch diameter rupture disk.

What size rupture disk is required if the water is saturated, i.e., T_o = 453 K ($\rho_{\ell,o} = 8.97 \bullet 10^2$ kg/m^3, $\rho_{v,o} = 5.16$ kg/m^3, $\lambda_o = 2.02 \bullet 10^6$ J/kg, $c_o = 4403$ J/kg-K).

$$G = 5.16 \bullet 2.02 \bullet 10^6 (4403 \bullet 453)^{-1/2}$$
$$= 7.38 \bullet 10^3 \bullet 0.62)$$

$$A = 100/(7.38 \bullet 10^3 \bullet 0.62)$$
$$= 2.19 \bullet 10^{-2} \; m^2 \quad or \quad 33.87 \; in^2$$

Answer: 8 inch diameter rupture disk, i.e., in absence of subcooling the required rupture disk diameter is significantly increased.

REFERENCES

ASME Boiler and Pressure Vessel Code, 1983, Section VIII, Div. 1, ASME, NY.

Fauske, H. K., 1988, "An Easy to Use Two-Phase Flow Model Including Subcooling, Non-Equilibrium and Viscous Effects," Proc. 2nd Int. Symp. on Runaway Reactions, Pressure Relief Design and Effluent Handling, March 11-13, New Orleans.

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