Experimental study on the depressurization of Freon at supercritical pressure

Ge ZHANG*, Naji H. A. AL-HAWSHABI, Yanhua YANG
School of Nuclear Science and Engineering, Shanghai Jiao Tong University, Shanghai, China

Abstract

The depressurization process of supercritical water has a significant influence on the safety of SCWR. The paper carried out the experimental study of the top and bottom vented blowdown processes of supercritical Freon(R134a). The investigation focuses on pressure and temperature transients. The effect of initial fluid conditions, orifice diameter on depressurization behavior was experimentally analyzed. During the isentropic change, it was observed that pressure at which two phases appear depends mainly on the initial fluid condition and depressurization mass flow rate.

Key words: Supercritical Freon, depressurization, visualization

1. Introduction

Depressurization, also known as blowdown process, is an interest subject of chemical and power industry. If the maximum operation pressure is larger than the designed one or the corrosion of the pressure vessels causes a breach, the pressure release is unavoidable. Therefore, the accurate prediction of the depressurization process is very important for the safety of the pressure vessels.

In one of the Gen IV nuclear reactors-Supercritical Water Reactor (SCWR), the supercritical fluid has been considered as the coolant. A loss-of-coolant accident (LOCA), which is a mode of failure for a nuclear reactor, of a SCWR would represent the typical depressurization progress. The depressurization progress of the supercritical fluid is like the ordinary blowdown progress, from one phase to two phases, with flashing phenomenon. But the properties of the fluid across the critical point are continues and change very rapidly. This difference makes the phenomenon interesting and varies from the subcritical depressurization.

During the last decades only a few data has been proposed for this situation. The United Kingdom Atomic Energy Authority (UKAEA)[1] had done some supercritical water discharge experiments. These experiments were conducted at the boundary of supercritical region to study the critical flow at the extreme pressure and temperature. Their experiments were conducted at a steady condition avoiding phase transition. Gebbeken and Eggers[2] of The Hamburg University of Technology (TUHH) conducted their work to analyze the evolution of supercritical CO2 in a vessel blowdown from initial supercritical condition. They focused on the pressure and temperature transitions in the vessel, including different axial positions. By using a gamma densitometer the phase separating and distribution were measured. Mignot[3-4] of The University of Wisconsin-Madison used different supercritical fluids, water, CO2, R22 and R134a to focus on the mass flow rate and depressurization from a pipe break through a small exit tube. The present study concerns the pressure and temperature of a vessel blowdown using R134a. An orifice flowmeter is used to control the mass flow rate.

2. Experimental Design

The experimental investigations consisted of pressure release experiment from initial supercritical conditions using Freon R134a. The critical data of R134a are P_{crit} = 4.06MPa and T_{crit} = 101.6°C.

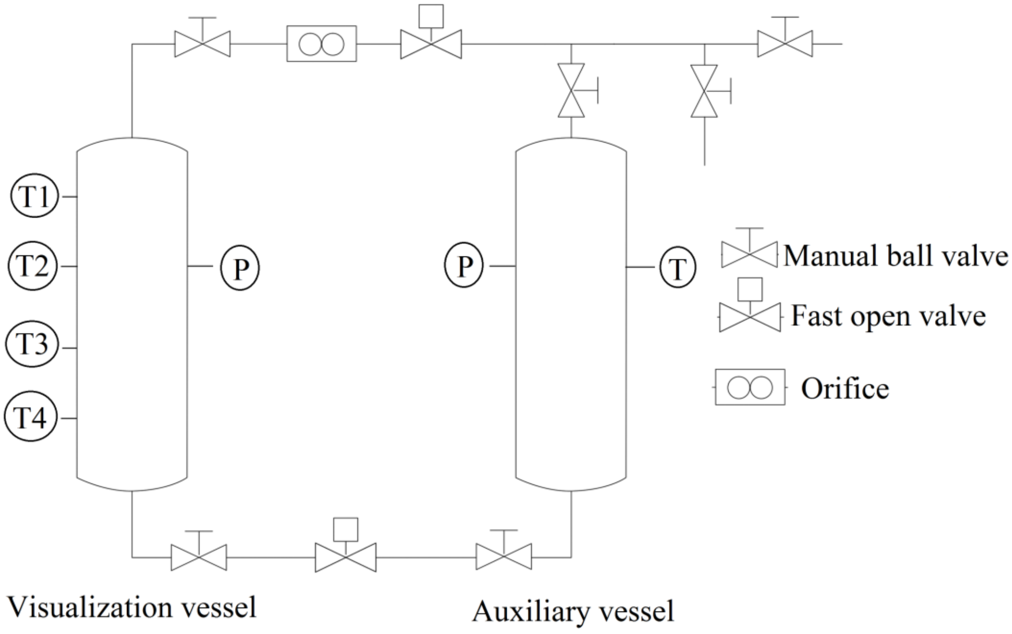


Figure 1 Sketch of experimental set up.

In Figure 1 a sketch of the experimental vessels is shown. Two cylindrical vessels are employed as the main parts for the storage of the R134a. The parameters of the two vessels are the same. The volume of the two vessels is V = 0.044m^3 for each. A system pressure up to P_{max}= 6MPa can be achieved. The inner diameter of the pressure vessel is D=0.257m, and the height is H= 0.8m. The visualization vessel is with two windows, one for photographic and video capture where the other one is for lighting. The visualization window is not very large because of the thermal and mechanical stress. The auxiliary vessel with no windows is used to supply the ambient pressure $P_{sat,30C}$= 0.77MPa. Two heaters were placed around the bottom of each vessel where the heat capacity for each heater is P_{heat}=3KW. The slowly heating from bottom, caused by the heat convection, can ensure the initial temperature gradient is lower than 0.1 °C. The two vessels are connected by two pipes, one from the top and the other pipe is from the bottom of the two vessels. Two pipes on the upper right are for the vacuum pump and R134a feeding pipe. Several manual ball valves are used to isolate the two vessels. A fast opening electromagnetic valve was located in the middle of each connecting pipe, which is used to assure the controlled initiation of the blowdown. The diameter of connecting pipes is 20mm, with an exchangeable orifice flowmeter. The optional orifice diameters are 8mm, 10mm, and 12mm.

Various measuring sensors are used to obtain information about the transient progress parameter. A pressure transducer is attached to the 2/3 height position of each vessel. It proved to be important to use a sensor with low signal deviation due to temperature change since large temperature changes occur during the depressurization process. From the previous experiment results, it was proved that the pressure gradient from the top to the bottom of the vessel could be neglected.

Four thermocouples (T type) with the outer diameter of d_T =1mm are installed to the center of the vessel along the vertical axis of each vessel. A tiny tube with inner diameter of d_{inner}=1.5mm is inserted to the center of the vessel, fixing the tail of the tube to the outer surface of the vessel. The thermocouple is inserted into the tube, which is as the pressure boundary between high pressure and the ambient. The positions of thermocouple from T1 to T4 is from H_1=0.2m, H_2=0.35m, H_3=0.5m and H_4=0.6m from the top of the vessel respectively.

An orifice-plate flowmeter with three different orifice plate diameters locates in the middle of the upper connecting pipe. A differential pressure transducer is attached to the orifice plate to obtain the mass flow rate of the transient.

All measuring signals are processed by an NI A/D convertor and a PC. The fast opening electromagnetic valve and a high speed camera are also controlled by this PC, assuring the synchronization. A acquisition frequency of f=1kHz is proved to be convenient for no losing any information.

3. Blowdown Map

Depending on the initial conditions, from the T-S diagram, different blowdown transient could be observed. Possible initial conditions are indicated by State A, State B and State C in Figure 2, where the little arrows in the figure indicate the initial isentropic blowdown process. The change of the fluid state during the depressurization could be considered as isentropic, because of the short time. At state A, because of thermal inertia of the vessel wall, the fluid temperature would drop to a limit, and the fluid remains in a single phase going from supercritical condition to subcritical superheated steam. At state B and state C a second phase appears. Assuming the transient is an isentropic change of state until saturated conditions are reached. Condensation occurs if the initial state is at state B whereas flashing will occur if the progress is initially from state C. This map shows the range of behaviors that could be expected to be observed during the depressurization. The state A and state B are investigated in the experiment presented in this paper.

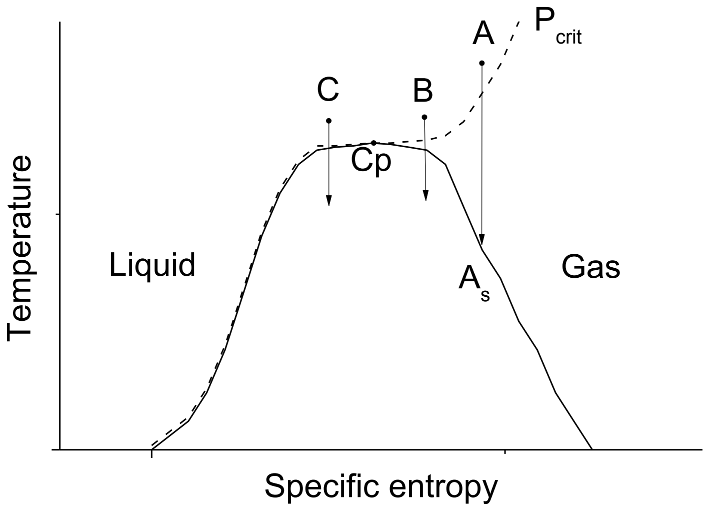


Figure 2 Blowdown map.

4. Results and Discussion

Experiments were accomplished for initial conditions that varied in temperature, pressure and minimum diameter of the orifice. The top and bottom blowdown were also conducted. The initial pressures were within the range of P_0=4.15-4.3MPa, whereas the initial temperature varied from T_0=102-104°C. This implied initial density in the range of ρ_0= 328-732 kg/m^3. All the initial conditions are near the critical point, representing the strongly change part of the property curve.

4.1 Pressure transients

In such a short time, the dissipative effects and wall heat transfer must be low and could be neglected. The pressure transient during a depressurization is shown in Figure 3. The fast opening electromagnetic valve was open at t_0= 2s. A steep pressure decrease can be observed during the blowdown. The steep drop has two parts, one is above the critical pressure going from the initial pressure and the other is below the critical pressure. The slope of first part is larger than the second one, as the dash line show in Figure 3. In the first part the fluid is in supercritical condition whereas in second part the fluid is in superheated steam. Because the compressible capacity of steam is large, the pressure drop slope is smaller than the supercritical part. At about 7.5s the pressure does not change significantly for several seconds. This is caused by the saturated condition is reached, which can be seen in Figure 4. Figure 4 shows the phase diagram of this transient. Later because of the continuous mass losing and wall heating, the pressure still decrease slowly while the temperature rises slowly.

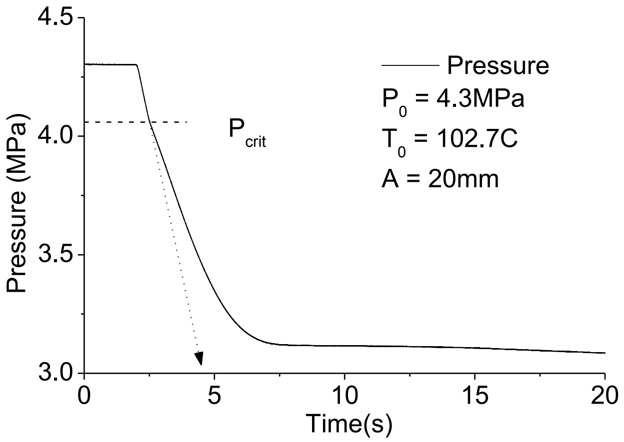


Figure 3 Pressure transient.

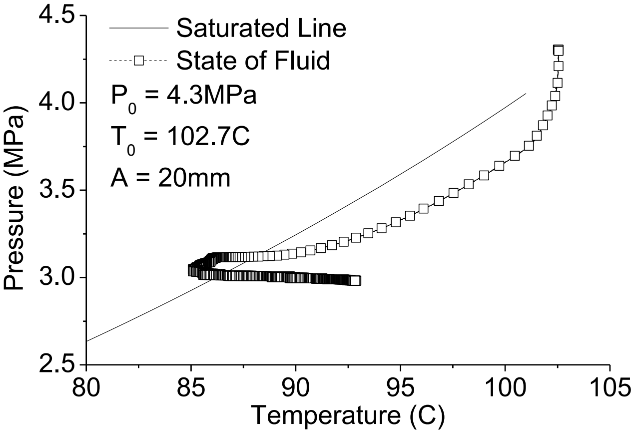
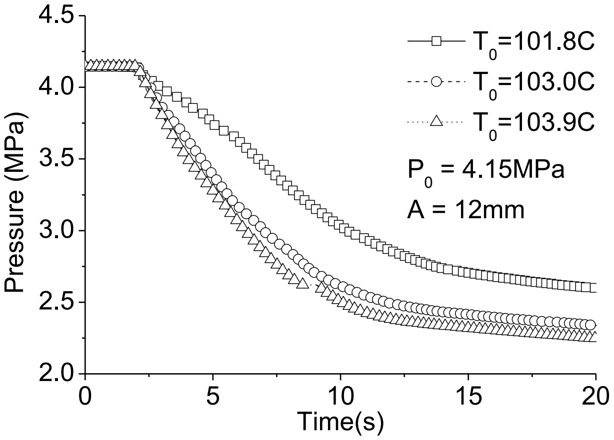


Figure 4 Phase diagram of pressure transient.

4.1.1 Initial conditions

The pressure transient strongly depends on initial conditions of the fluid. Figure 5 shows the pressure transient as a function of time for various initial temperatures. The initial pressure is chosen to be P_0=4.15MPa and the orifice diameter is A=12mm. During the blowdown progress, it is hard to separate the three lines above the critical pressure. Their pressures decrease with the same rate until they cross the critical pressure. In Figure 2 it can be indicated that the lower temperature initial conditions of Point A is, the higher saturated pressure of Point A_s would reach through the isentropic process. Then in Figure 6 it shows the different saturated points they reached. Because of the auxiliary vessel has the same volume as the visualization vessel. The fluid in the experiment can’t easily cross the saturated line. It goes back to the superheated steam phase by the residual heat of the wall.



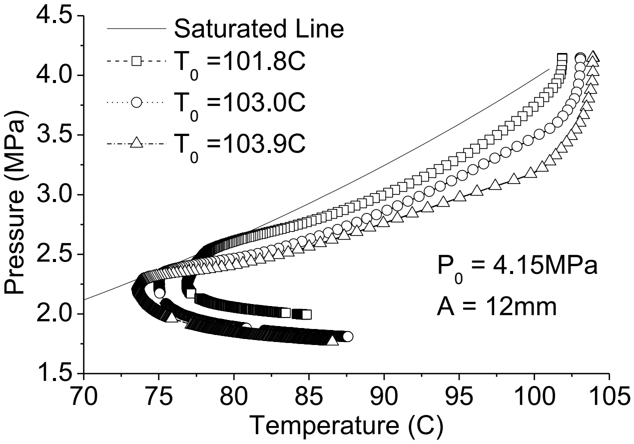
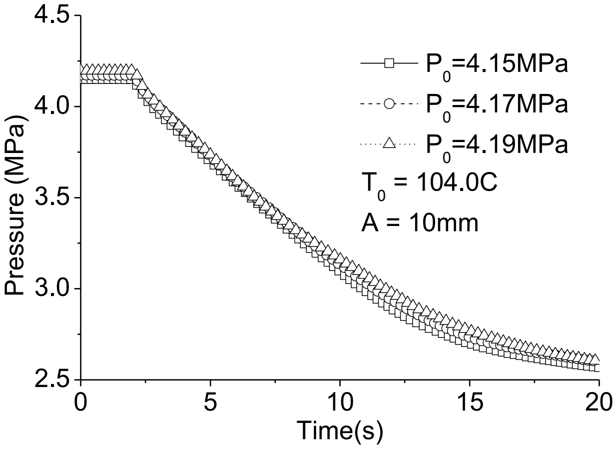


Figure 5 Pressure transient, various initial fluid temperatures.

Figure 6 Phase diagram of pressure transient, various initial fluid temperatures.

The effect of various initial pressures on the pressure transient can be shown in Figure 7. The initial temperature is T_0=104°C and the orifice diameter is A=10mm. In both Figure 7 and Figure 8 it is observed that the different initial pressure has little influence on the pressure transient. From Figure 8, when the initial pressures drop rapidly to the critical pressure, the initial temperatures almost do not change, so the fluids come to a same point on the critical pressure line. The blowdown process above the critical pressure is more like an isothermal progress, while the blowdown below the critical pressure is an isentropic process. Finally they reach the same saturated point.



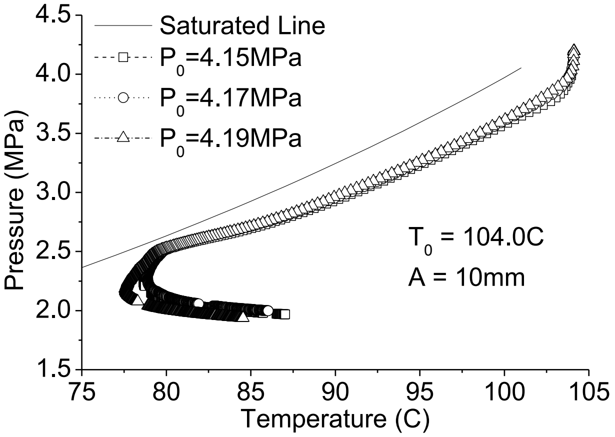


Figure 7 Pressure transient, various initial fluid pressures.

Figure 8 Phase diagram of pressure transient, various initial fluid pressures.

4.1.2 Orifice diameter

The larger the orifice diameter is, the more outgoing mass flow from the vessel. In Figure 9 it shows the pressure transient for different orifice diameters. The initial pressure is P_0=4.15MPa and temperature is T_0=104°C. It can be seen that the pressure drops faster for a larger orifice diameter.

Even above the critical pressure, the pressure decrement rate is different for different orifice diameters.

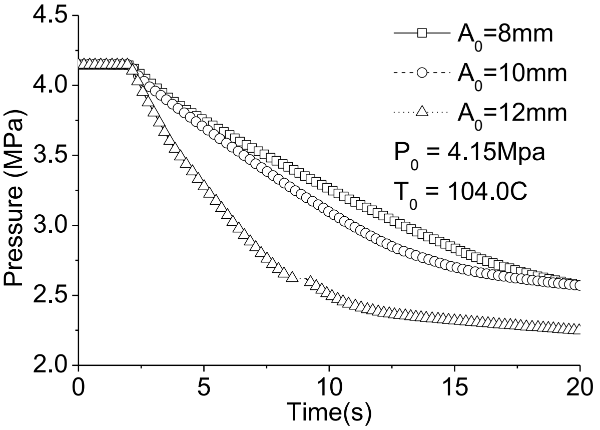
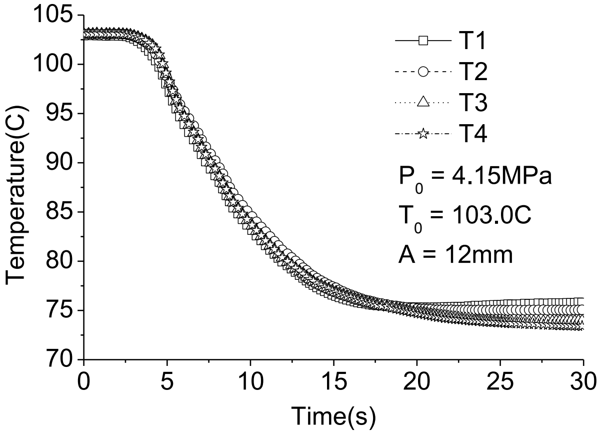


Figure 9 Pressure transient, various orifice diameters.

4.2 Axial temperature

A significant decrease of the fluid temperature was observed during the depressurization process. Figure 10 shows the measured temperature with respect to time for various axial levels. As mentioned above, there are four thermocouples installed at various axial positions in the center of the vessel. The initial condition of fluid for this case is P_0=4.15MPa and temperature is T_0=103°C. The diameter of the orifice is A=12mm.



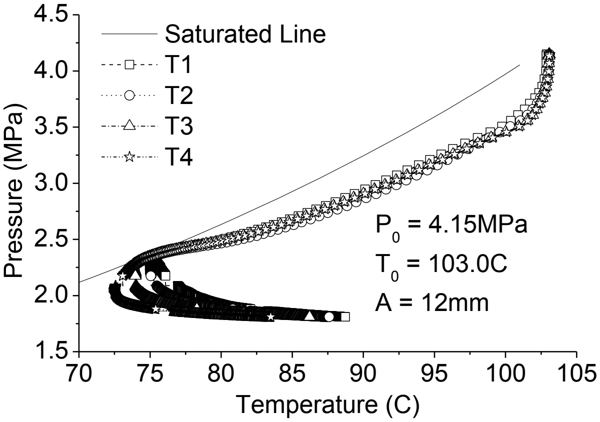


Figure 10 Axial temperatures transient.

Figure 11 Phase diagram of axial temperatures transient.

During the depressurization a delay of the temperature occurs after the pressure decrease.. But the temperature begins to drop at about t_T= 2.5s. The temperature decrease is a result of the change of the thermodynamic equilibrium state according to fluid density and pressure. And the 1mm thermocouples have a delay of the response of the temperature change. This two reasons lead to the delay of the temperature. The temperature curve decreases smoothly, not like the steep drop of pressure. During the blowdown process, no axial temperature gradients were measured until approximately t=17s. From Figure 11 it can be observed that as the fluid reaches the saturated line, because of the residual heat from the wall, which heats up the fluid inside the vessel, the top temperature increases relatively greater than the one below for all the temperature gradients.

5. Conclusion

Experimental investigations of depressurization processes of supercritical Freon (R134a) are presented. The initial conditions are in state A and state B regions (Figure 2). The fluid goes from supercritical phase to superheated vapor, and then to vapor/liquid two phases. Thermohydraulic phenomena were discussed, particularly the pressure transient and the axial temperature distribution.

The pressure transient is divided into two parts, one above the critical pressure and another below the critical pressure. The blowdown above the critical pressure is more like an isothermal process, while below the critical pressure it is an isentropic process. So the initial temperature influences the pressure drop significantly whereas the initial pressure has little influence. The diameter of the orifice determines the pressure drop rate, for both supercritical and subcritical parts.

The temperature decrease has a delay of time relative to the pressure transient. During the blowdown process, no axial temperature gradients were measured until the fluid reaches the saturation line. The temperature gradient appears because of the residual heat from the wall.

It would need further investigations on depressurization processes of the state C. And the visualization images would be got for more information to know more details about the progress.

6. Acknowledgement

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