Initial Study of Supercritical Fluid Blowdown

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Initial Study of Supercritical Fluid Blowdown

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The behavior of supercritical (SC) fluid during a blowdown is under investigation. A model based on a steady state Homogeneous Equilibrium Model (HEM) and conditions with and without friction is presented. Calculations indicating three different possible regimes in a blowdown scenario are calculated with this model. The single-phase flow in the supercritical region and the transition either into sub-cooled water, a two-phase fluid or a superheated gas near the critical point results in an interesting flow with a wide range of behavior. Depending on the initial conditions and the geometry either vaporization or condensation can occur either in the pipe or at the exit. In addition, these results are to be extended to other fluids like CO_2, R22 or R134a by comparing thermodynamic properties and their dynamic evolution to dimensionless SC water results. Finally the design of an experiment with initial data on the depressurization of a supercritical water system is presented.

I. INTRODUCTION

Advanced power cycles are investigating supercritical (SC) fluids to optimize efficiency. The motivation of this trend is based on three major reasons. First, by using a SC fluid, as a single-phase fluid, there is no concern about the heat transfer discontinuities; e.g., critical heat flux. Secondly, it reduces the required mass flow substantially per unit of thermal power required. Finally this simplifies the power cycle, as fewer components are required (in particular phase separators). Unfortunately these improvements do not come without any disadvantages. In the direct power cycle designs the loss of flow transient becomes a major concern in the operation and risk assessment of the reactor. A loss of flow can be caused by pump stoppage or a pipe rupture. In both cases the relevant parameter will be the characteristic time of depressurization, as this will specify the type of response to adapt and control the transient event.

Since these possible transients have to be well understood the University of Wisconsin has initiated a study to characterize the critical mass flow rate of different supercritical fluids under a large range of temperature and pressure. An initial calculation has been done to evaluate different behaviors of the supercritical fluid in a blowdown event and to design the experiments that are to be performed.

II. REVIEW AND INITIAL CALCULATION

II.A. Past Studies

The only data the authors found concerning the event of supercritical water blowdown was the work conducted by the United Kingdom Atomic Energy Authority (UKAEA)[1]. These experiments were however conducted at the boundary of the supercritical region (temperature lower than 400 °C) in order to study the critical flow at the extreme pressure and temperature attained during an Anticipated Transient Without Scram (ATWS) event rather than at possible accident conditions for the current advanced power cycle. Their experiments were conducted at steady state conditions avoiding phase transition. In addition to this study the University of Hamburg conducted work to characterize the evolution of supercritical CO_2 in a vessel during blowdown [2]. In this paper they focused on the void fraction and phase separation during the blowdown for chemical plant safety issues. Of more concern in the present study are the mass flow rate and the depressurization from a pipe break.

II.B Initial calculations

I.B.1.Blowdown Model

In an effort to analyze this problem a standard Homogeneous Equilibrium Model (HEM) was implemented into an Engineering Equations Solver (EES)[3] along with data for the steam IAPWS [4] and CO_2 [5] thermodynamic properties. The calculation was performed on a reservoir at an initial pressure and temperature that depressurizes through a straight vent line. The critical flow rate was computed for a large range of initial conditions – $400<T<600$ °C and $25<P<37$ MPa with and without friction. The model uses compressible gas dynamic equations while the fluid is in single phase and implements a standard HEM when a second phase appears during the blowdown event. The HEM assumes thermal equilibrium between the phases and the same velocity in the pipe, which leads to an underestimation of the critical flow. The results are however useful for the design of an experiment and as a first approximation of the mass flow to determine the depressurization rate.

I.B.2.Blowdown map

Depending upon the initial conditions (Temperature range is 400-600ºC and pressure 25-37Mpa) three regions of behavior have been observed. The first region (region 1 shown in Fig. 1) the fluid remains in a single phase during the blowdown event going from supercritical condition to subcritical superheated steam. In the second and third regions a second phase appears. Condensation is expected in region 2 whereas vaporization occurs in region 3. This map shows the range of behaviors that could be expected to be observed during a blowdown event. In a typical power cycle operating with a SC fluid any of these regimes could exist and thus it is necessary to understand the specifics of depressurization from each region.

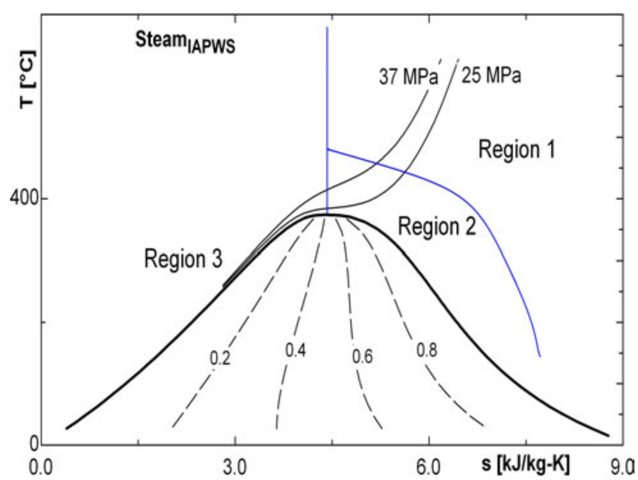

Fig. 1. Blowdown map depicted in a temperature entropy diagram

II.COMPARISON OF THE CALCULATION WITH UKAEA DATA

In an effort to initially validate our model, calculations were performed at the same initial conditions as those of the UKAEA experimental data (374 to 400ºC and 22 to 31 Mpa). In these experiments four different exiting nozzles were considered. The data obtained with the Nozzle C (baffled orifice) are not discussed since it is not relevant to the presented work. Nozzle A is a sharp edge 1.7mm diameter orifice. Nozzle B and D are round edge short nozzles with similar length to diameter ratios. Nozzle B has a 1.7 mm diameter whereas nozzle D has a 2.5mm diameter. At this stage of calculation the model does not take into account the geometry of the nozzles and an isentropic flow assumption is implemented. The results of these experiments and the current calculations were also compared to calculations performed with the RETRAN code. The results depicted in figure 2 show a reasonable agreement between the current model (EES), and RETRAN code, however for high mass flow rate both models diverge from the experimental data.

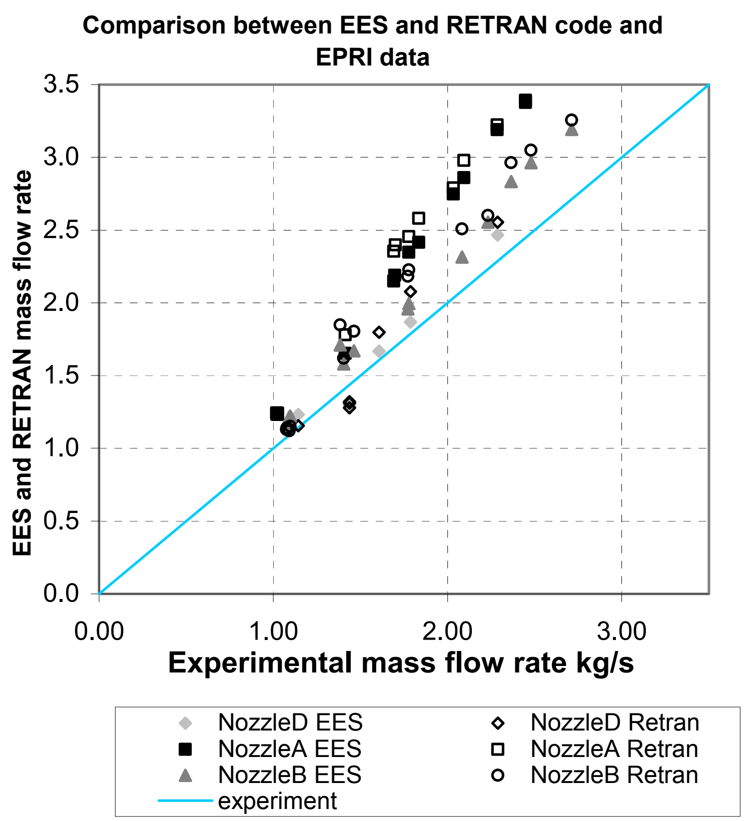

Fig.2. Comparison of EES Code with Retran calculation and data from UKAEA

The calculated mass flow rates are higher than experimental mass flow rates due to the isentropic flow assumption made in the EES model. Because of the friction the mass flow rate would decrease, explaining the trend. Two trends can also be pointed out corresponding to the geometries of the nozzle used during the experiment. Nozzle A diverges from the experiments more than the short nozzles B and D. The difference between the simulations and the experiment suggest a secondary effect due to the geometry of the nozzle. The sharp edge orifice A has a higher entrance pressure loss

inducing an additional friction component that tends to reduce the critical mass flow compared to the round edge entrance nozzles B and D.
Both the experiment and theory suggest that the higher the pressure and the lower the temperature the higher the mass flow rate. As the mass flow rate increases the error between calculation and experiment increases. This is due to the fact that as the mass flow increase the friction effects becomes more significant

III. COMPARISON BETWEEN SUPERCRITICAL FLUIDS

III.A. Thermodynamic properties comparison

A study of non-dimensional properties for various supercritical fluids such as enthalpy or entropy (Fig. 3) shows a similarity of the saturated vapor line between R22, R134a and Water. None of these fluids seem to match the saturated liquid line of H_2O. The thermodynamic properties of CO_2 show a large difference with the three other fluids. From these plots suggests a different dynamic behavior relative to the appearance of the second phase during a blowdown event. For the CO_2 a second phase can appear at higher T* than for H_2O, R134a or R22.

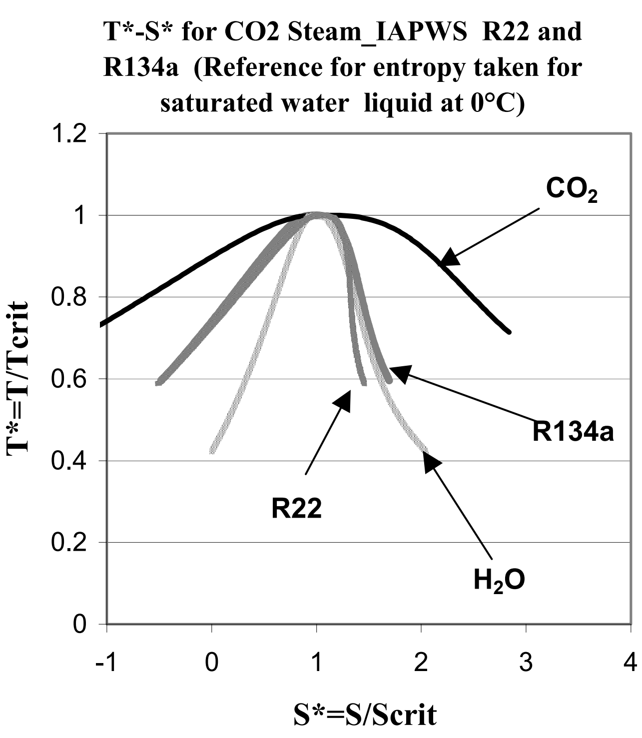

Fig.3. Comparison of saturated lines for different fluids.

III.B. Dynamic evolution during blowdown process

Based on the thermodynamic properties and Figure 3 one would be compelled to assume that CO_2 behaves quite differently than water. A dynamic calculation of the evolution of the pressure and temperature in a vessel during a blowdown event however shows a different result. As a matter of comparison we calculated the characteristic time from similar initial conditions for the fluid to enter into the two-phase dome assuming an isentropic process. The results of this analysis are shown in figure 4 for a given vessel volume with different diameter orifices.

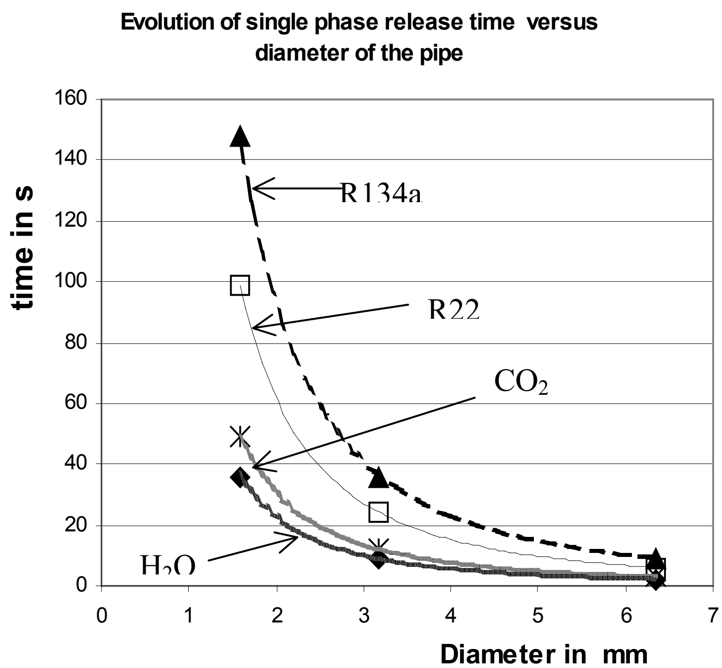

Fig.4. Characteristic time of fluid remaining in a single-phase flow from SC condition. Volume=0.1m^3.

It is interesting to note that this characteristic time t_{SC} is inversely proportional to the square of diameter d of the orifice. An additional analysis was conducted with a constant diameter and variable vessel volume and it was found that the depressurization time was linearly dependant on the volume. The single-phase depressurization time can be expressed by:

$$t_{SC} = C * \frac{V}{d^2}$$

Where t_{SC} is the decay time measured in seconds, V is the Volume of the blowdown vessel, d the pipe diameter and C is a constant depending on the fluid which are tabulated in table 1.

Fluid	H_2O	CO_2	R22	R134a
Constant C	$9{,}18.10^{-4}$	$1{,}24\ 10^{-3}$	$2{,}51.10^{-3}$	$3{,}7.10^{-3}$

Table.1. Value of the constant C depending upon the fluid

IV.EXPERIMENTAL DESIGN

A blowdown experiment was designed which makes use of a SC water loop at the University of Wisconsin to measure the mass flow rate for a large range of temperatures and pressures. The experiment consists of releasing the SC water through an uninterrupted tube at the exit of which the density and the temperature are measured via a laser system. The experiment was constructed such that the inner diameter of the exit tube was as uniform as possible to ensure critical flow occurred at the exit of the tube and to simplify the analysis of the experiments. The reaction force due to the impact of the SC water jet was measured on a force transducer mounted to a thermally isolated plate. Measurement of this force along with the density at the exit allows the determination of the mass flow $\dot{m}$ as a function of time based on the following equation:

$$\dot{m} = \sqrt{\rho_{exit} * A * \left(F - \left(P_{exit} - P_{atm}\right)A\right)}$$

where A is the cross sectional area of the pipe, P_{exit} and P_{atm} are the pressure at the exit of the pipe and the atmospheric pressure, F is the measured force and ρ_{exit} the density of the water.

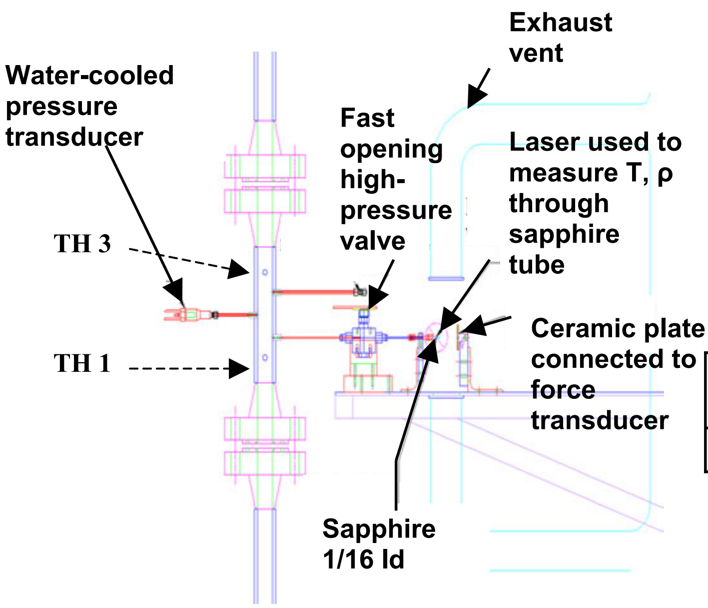

Fig.5. Experimental design of transient SC water blowdown.

V. PRELIMARY RESULTS.

A preliminary set of experiments has been conducted to scope the proper operation of the experiment. The initial pressure was 25 MPa (3600Psi) and the initial temperature was 500ºC.The inner diameter of the exit tube was of 1.59mm (1/16 in). The evolution of pressure and temperature in the loop was measured to evaluate the time to depressurize from the initial supercritical condition to a subcritical pressure. Figures 6 and 7 show the pressure and the temperature evolution in the loop versus the time respectively. In figure 6 the gray line represents the estimated depressurization based on the calculated mass flow rate of the isentropic model without friction. It is evident that the effect of friction is extremely important to the estimation of transient depressurization. The depressurization times from SC conditions to subcritical pressure are tabulated in table 2.

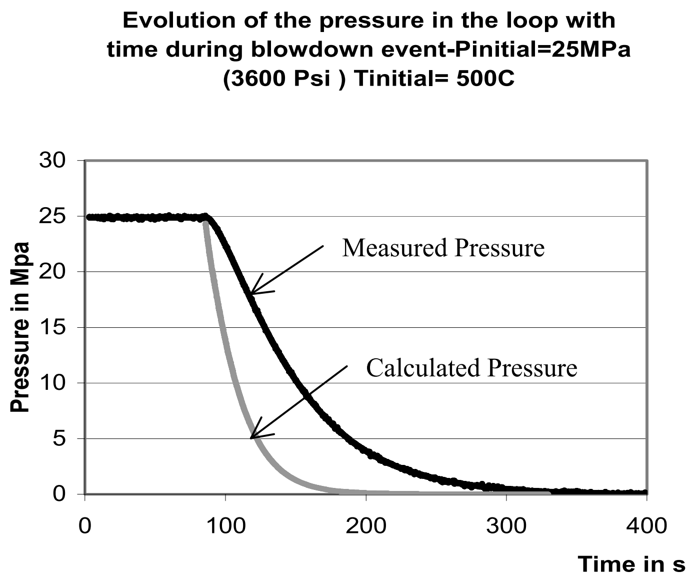

Fig.6. Pressure evolution during the depressurization of the loop compared to the calculation with EES

	Frictionless calculation	Run1	Run2 *	Run3
Time	2.36	15.31	16.99	15.40

Table.2. Relief time from SC to subcritical condition in pressure

Three experiments were conducted at the same conditions to ensure reproducibility of the results. Two conclusions are to be pointed out. First, the friction plays a dominant role as the measured depressurization time is much higher

* R
pip
fric

than that calculated by the isentropic HEM model (by a factor of 6). Secondly, the experiment is highly reproducible.
Our initial calculations were performed considering an isentropic evolution in the loop however as heat is added to reach the supercritical initial conditions it cannot be considered isentropic. Actually heaters were shutting down before the blowdown is initiated but the heat inertia of the loop keeps the temperature of the water high enough to avoid the appearance of the second phase that we expected initially. The temperature plots shown in figure 7 measured relative to the exit tube as indicated on figure 5 show a temperature jump around 90 seconds after the start of the depressurization. This effect is still under investigation.

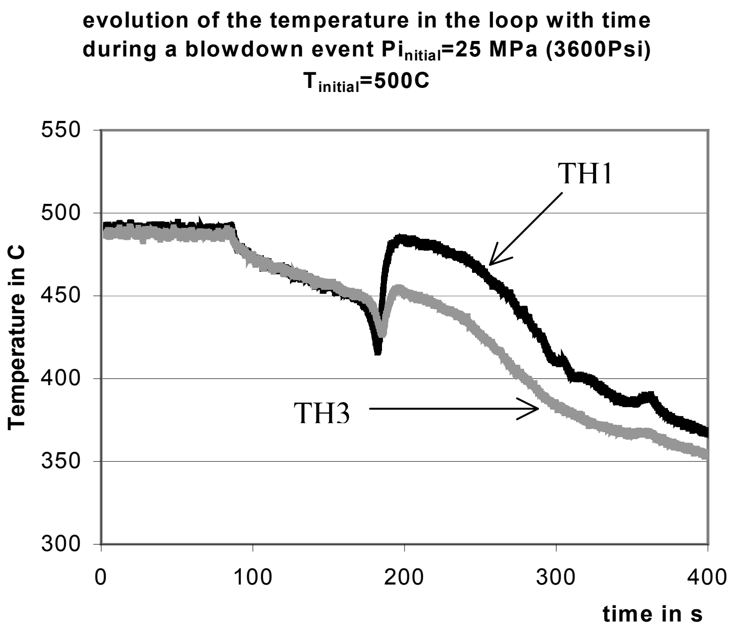

Fig.7. Temperature evolution during the depressurization of the loop

VI. CONCLUSIONS

The simple HEM model implemented in EES shows good agreement with the UKAEA RETRAN calculation. Both Simulations over predicted the test data for mass flow by as much as 40% for the orifice nozzle A and as much as 25% for the short nozzle B and D. This discrepancy is attributed to frictional effects. Pursuing the calculations a map of behaviors was obtained for supercritical water depending on the initial conditions ranging from 400 to 600C and 25 to 37MPa. A comparison between thermodynamic properties and the dynamic evolution of SC fluids show controversial results as to whether SC CO_2 will behave like water. Finally the experiment is set up for SC water blowdown to observe the behavior under real conditions for different pressures and temperatures. The preliminary experiments show good reproducibility and a dominant effect of the friction on the critical flow.

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