EMERGENCY VENTING OF PRESSURE VESSELS

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1. Introduction

The runaway of exothermal chemical batch reactions may under unfavorable conditions result in uncontrolled releases of toxic, funable and explosive substances. By a runaway exothermal reaction or unintentional external heating the temperature in the pressure vessel increases. In order to prevent an overpressure in the vessel and so damaging of the equipment most chemical reactors, storage tanks and other process vessels are equipped with a rupture disc or an emergency relief valve. The pressure reliefs or safety valves have to be designed for a flow rate, which guarantees that no inadmissible pressure increase occurs in the vessel. So the vessel can be vented through the safety device at a sufficiently high rate to compensate the rate of pressurization. The vented toxic or explosive substances have to be collected in a retention system.

2. Phenomena during depressurization

During emergency venting of a pressure vessel complicated thermodynamic and fluid-dynamic processes take place [1]. Normally the vessel is partially filled with a saturated liquid or completely with a vapour-liquid mixture. The gaseous and the liquid phase are in thermodynamic equilibrium. When the vessel is depressurized, first vapour enters the relief device. This causes a rapid decrease of the pressure in the vessel as to be seen in Fig. 1 [2]. Thermodynamic non-equilibrium occurs between liquid and vapour. By flashing evaporation and phase separation in the superheated liquid, bubbles of vapour are generated. They rise in the liquid and disengage at the surface. Whilst the bubbles remain in the liquid during fast depressurization, they cause an increase of the liquid level. As the mixture level can rise up to the vent, two-phase flow may enter the relief device. The flow behaviour of the two-phase mixture through the relief device differs from that

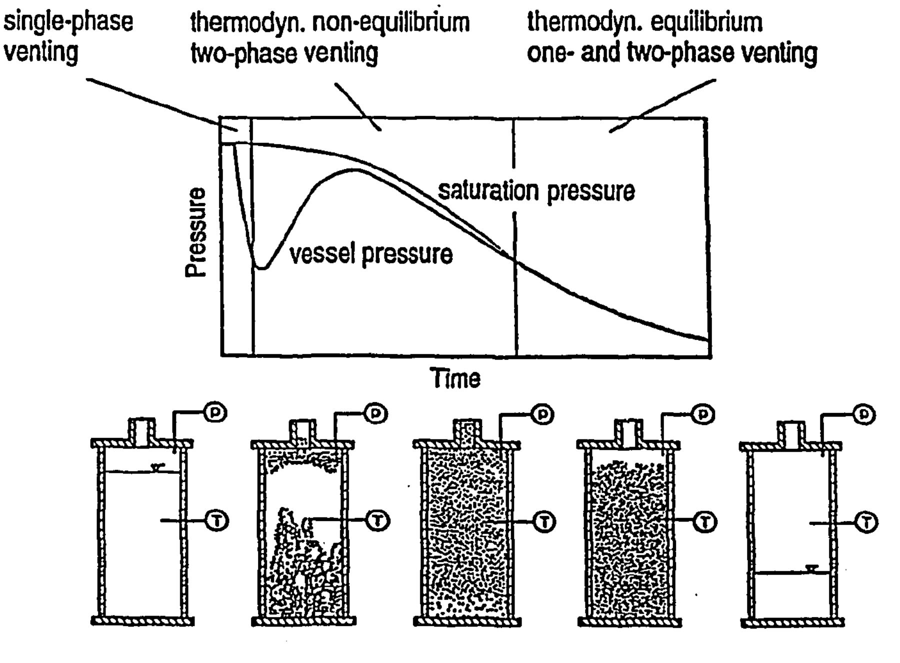

Fig. 1 Hydrodynamic processes during emergency venting

of the single-phase. It is strongly de- pendent on the amount of liquid carried in the gas or vapour flow. The composition of the two-phase mixture influences the pressure drop and the maximum flow rate through the valve, the so-called critical flow. The volumetric flow rate of the released two-phase mixture can be smaller than the volumetric flow rate of vapour produced in the vessel. For this reason the pressure may even recover for a short period. By vaporization thermodynamic equilibrium between vapour and liquid is reached again. The venting causes the decrease of mass in the vessel and so the decrease of the mixture level. The depressurization process ends with single-phase vapour venting.

3. Codes for modelling emergency venting

In order to describe the thermo- and fluiddynamic processes during depressurization experimental and theoretical investigations are carried out. The investigations are aiming to model the venting process and to determine the necessary size of the relief vent. Therefore, several numerical models can be used, which are suitable for the analysis of venting transients. In order to compare different models Skouloudis [3] made a benchmark exercise focused on the hydrodynamic aspects of the venting of non-reacting fluids. The experimental data, which were analysed in this benchmark, were carried out at different plants. From the codes applied to analyse the benchmark data the discussion below only refers to the results obtained with RELAP and VESSEL. In order to compare these codes with the code ATHLET calculations are carried out for certain experiments. The codes use different types of two-phase flow models. They dispose of closure relationships, which depend on the flow pattern of the two-phase mixture, but relate the two-phase flow parameters to each other through the mass, momentum and energy conservation equations in different ways.

RELAP and ATHLET are developed to assess the safety of nuclear installations. Based on a one-dimensional approach they describe transient single- and two-phase flow regimes in complex vessel and pipe systems. The non-homogeneous non-equilibrium model for the two-phase system is mapped as system of ordinary differential equations. RELAP5 is developed by the Idaho National Engineering Laboratory (INEL) for the U.S. Nuclear Regulatory Commision (NRC). RELAP5/Mod1 uses separate mass and momentum equations for the individual phase to treat two-phase flow conditions. Due to the assumption that the dominating phase always saturates the minor one, only one energy equation is needed for the two-phase mixture. The selected approach can describe conditions of non-homogeneous flow with different velocities of both phases and thermal non-equilibrium effects during evaporation and condensation. The code includes the description of one-dimensional heat conduction in the vessel wall and the heat transfer between the solid vessel wall and the fluid.

The system code ATHLET is developed by the German Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) for best-estimate analysis in reactor safety [4]. The realistic simulation of two-phase flow and heat transfer phenomena requires detailed models and comprehensive description of the reactor cooling system. The version of the code applied here is built on the five equations thermodynamic non-equilibrium model. There is one mass and one energy equation for each phase, but only one momentum equation for the two-phase mixture. The velocity difference between the two phases is determined by a full-range drift-flux model. Within the non-homogeneous control volume a mixture level is modelled. Above the mixture level a droplet layer is assumed, below the mixture level vapour is modelled as single bubbles surrounded by the liquid.

The code VESSEL is under development at the Joint Research Centre (JRC) Ispra. As used for the benchmark, the pressure vessel can be discretized into several control volumes with a single control volume for the vent line. VESSEL is capable of handling chemical reactions of arbitrary order and can describe the vent line hydrodynamics. External heat transfer through the vessel and the vent line can also be included. Thermal equilibrium has been assumed between the phases. The pressure drop in the vessel due to friction and acceleration forces is neglected. A drift-flux constitutive law relates the momentum of the second phase. The kinetic energy and axial conduction terms in the energy equation are also assumed to be negligible. The mass flow in the vent line is modelled in a simplified manner, taking into account blowdown experiments which were performed at the JRC. The mass flow in both the supercritical and subcritical regions is approximated similar to the gas dynamic theory.

4. Experimental Set-up

The aim of the experimental tests chosen for the benchmark is to describe the phenomena and to demonstrate the importance of some of the parameters related to the venting. The data were generated in depressurization experiments of different liquids without any chemical reaction taken place in the vessel. The experiment this paper refers to was performed in a 280l pressure vessel shown in Fig. 2 [3]. The height of the vessel used in this experiments is 4.27m, the diameter is 0.30m. The diameter of the blow-down orifice is 13mm. Before starting the experiments the vessel was filled with demineralized water up to nearly two-thirds of its height and boiled at atmospheric pressure for 30 minutes to free the supply water from any dissolved gas. The vent on top of the vessel was then closed and the water was heated up to the starting conditions at 385°C and 7MPa. Blow-down was initiated by opening the valve.

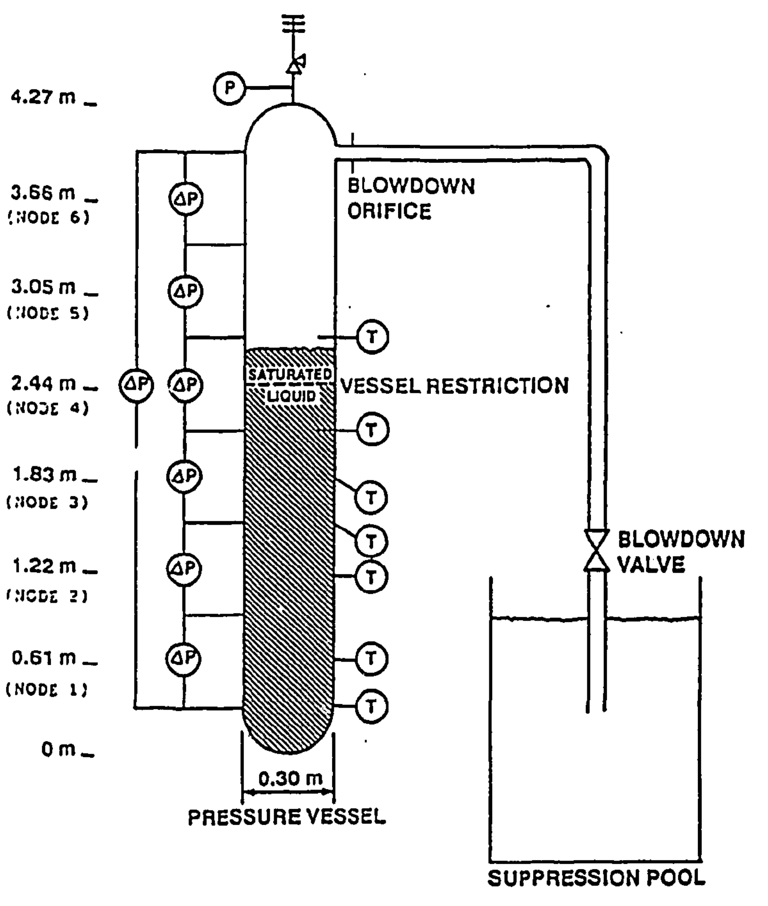

Fig. 2 Experimental set-up

5. Results

In Fig. 3 the measured and calculated pressure in the vessel is shown. The pressure drop in the vessel is measured by the pressure transducer placed on top of the vessel. As mentioned before the pressure in the vessel decreases rapidly after opening the valve. The comparison of experimental and calculated data show that the pressure decrease is almost perfectly described by the code VESSEL. RELAP and ATHLET provide to low values. The high accuracy of the data calculated by VESSEL is due to the consideration of initial void fraction in the vessel.

As shown in Fig. 4 the mixture level in the vessel does not reach the relief valve placed on top of the vessel at 4.27m. During depressurization only vapour is vented out of the vessel. The evaporation starts with opening the relief. After about 5s the mixture level has reached its maximum and then decreases continously.

In Fig. 5 the measured void fraction in different levels of the vessel are compared with ATHLET results. For the calculation with ATHLET the vessel is discretized into six equal sized nodes beginning at the bottom of the vessel (see Fig. 2). In node 2 the initial void fraction is zero and rises up to 30% for both the experiment and the calculation. Node 4 is the volume directly below the initial water level. Due to the rising mixture level the void fraction in this node increases up to 40%. As a consequent of

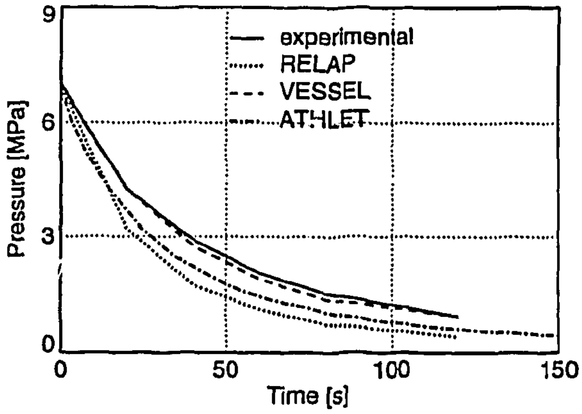

Fig. 3 Time dependent pressure in the vessel

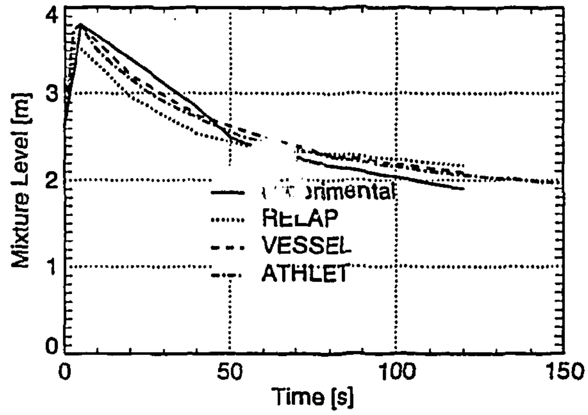

Fig. 4 Time dependent mixture level in the vessel

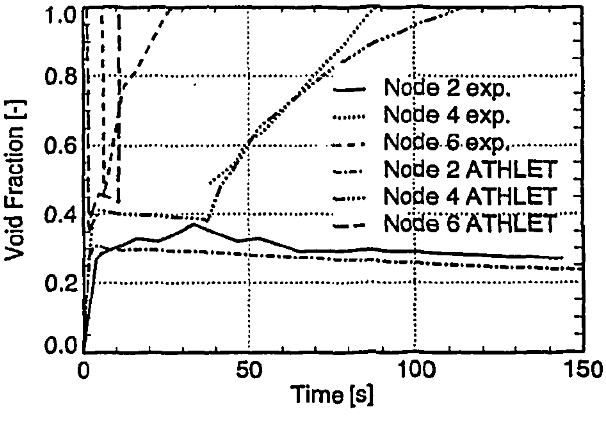

Fig. 5 Time dependent void fraction in different heights of the vessel

the water losses during venting the final level is decreased below of node 4 and there is pure vapour in that node at the end of the experiment. Node 6 already contains vapour at the beginnig. Due to the rising mixture level the void fraction decreases to 45% for a short period.

6. Conclusions

Depressurization through safety and pressure relief valves has gained increasing interest in safety stategies for chemical plants. To prevent runaway reactions the apparatus have to be equipped with safety reliefs. The layout of the venting equipment requires reliable and precise data of the fluid- and thermodynamic processes during depressurization. With the numerical codes developed for safety analysis the venting of steam vessel can be simulated. ATHLET especially is able to predict the void fraction depending on the vessel height. Although these codes contain a one-dimensional model they allow the description of complex geometries due to the detailed nodalization of the considered apparatus. In chemical reactors, however, the venting process is not only influenced by the flashing behaviour but additionally by the running chemical reaction in the vessel. Therefore the codes used for modelling have to consider the kinetics of the chemical reaction. Further multi-component systems and dissolving processes have to be regarded. In order to predict the fluid- and thermodynamic process it could be helpful to use 3-dimensional codes in combination with the one-dimensional codes as used in nuclear industry to get a more detailed describtion of the running processes.

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