THE STATE OF THERMOHYDRAULIC UNDERSTANDING OF PRESSURE RELEASE PHENOMENA

1. Definition of Problem

Pressure release of an apparaturs or a vessel can occur voluntary via valves or burst disks to avoid a not allowable overpressure for example due to an uncontrolled chemical reaction. It, however, can also happen non-voluntary by pipe leakages or cracks at vessel nozzles. The release occurance in the vessel and by this also the flow velocity at the outlet can be exactly and reliably calculated for gases with the laws of gas dynamics. However, if liquid is contained in the vessel, it is wellknown that one has to distinguish whether this liquid may evaporate partially due to its thermodynamic properties during the expansion from the pressure in the vessel at the beginning to the ambient pressure or whether the boiling temperature of the fluid at the end of the pressure release is higher than the temperature in the vessel which depending from the liquid level and the position of the leakage may produce a single phase outflow. Because of the high sound velocities in liquids the mass flow of pure liquids out of a nozzle or a crack can be calculated with the simple Bernoulli-equation.

With two-phase - gas/liquid - flows the thermodynamic and hydrodynamic interactions are much more complicated. The pressure release in a vessel which is filled with liquid or vapour which undergoes the saturation condition, i.e. the the thermodynamic equilibrium between vapour and liquid, always causes as shown in the temperature-entropy diagram of fig. 1 a, two-phase mixture. In the saturated liquid vapour bubbles are produced by flashing and during the expansion of saturated vapour liquid droplets are condensing. Both phase changes are combined with high energy transport between the phases - liquid and vapour - and need a finite driving force to be started which is wellknown as boiling delay or condensation delay. Pressure release in fluids - gas/liquids mixtures - being in thermodynamic saturation condition therefore always causes at first and for a short period unstable conditions whereas a pressure increase starting from the saturation line produces a subcooling of the liquid or correspondingly a superheating of the vapour which is stabilizing the thermodynamic condiditon.

For an intended pressure release the crossection of the valve or the burst disk must be so designed that the volume decrease due to the flow is compensating the volumetric expansion in the vessel due to exothermal reaction or due to heat input from outside to avoid an unallowable pressure in the vessel. For the layout of these release openings the velocities and the density of the vapour / liquid mixture must be wellknown at the narrowest opening or another flow limiting position of the expansion line.

The thermo- and fluiddynamic conditions, however, are depending from the history which the fluid is undergoing on its way to the outlet opening during the expansion. Thereby one has to take in account a very complicated interaction between the change of thermodynamic state and the fluiddynamic parameters. Phenomena strongly influencing the mass flow rate are especially

- boiling delay in the liquid
- vapour separation during the foaming in connection with the flashing and
- critical flow velocity or better, critical mass flow rate in the outlet opening.

In case of several interconnected apparatus as it is usual in plants of chemical engineering and power engineering mass flow rates between the components have to be taken in account and by this very complicated fluiddynamic occurences in the combining parts of the system and in the sections of the different apparatus.

2. Flashing in vessels

We will discuss now the pressure release using as an example a vessel which is in the lower part filled with saturated liquid and at the upper part with vapour. With this example we will explain phenomenologically and qualitatively the fluiddynamic condition at a release valve having its position at the top of the vessel. As demonstrated in fig. 2 there are created vapour bubbles in the liquid phase during the first period of the pressure release which - if the liquid was without boiling nuclei - are formed namely in the areas near to the surface. With nuclei, however, they are equally distributed over the total hight of the liquid. This flashing is enlarging the volume of the liquid and the liquid level is increasing. Almost simultaneously or only a little retarded droplets occur in the gas phase which were carried over by the gas bubbles, leaving the liquid or which may also originate from expansion-condensation.

The ongoing behaviour of the swell level of the liquid is then mainly controlled by the relative velocity between the gas bubbles and the liquid. This relative movement between the phases is again depending on thermodynamic properties like surface tension and viscosity, however, also on the time course of the pressure release. In case that the bubbles could freely arise and by this separate from the liquid, the swell level never would reach the upper end of the vessel. With a fast expansion, however, the phase separation is to slow - i.e. there is more vapour produced than can escape through the liquid upwards - and the two-phase mixture is foaming so violently that large liquid masses are reaching the release valve. This has an important influence to the mass flow through the valve.

Quantitatively the foaming, the phase separation and by this the thermodynamic condition in the vessel during the pressure release can be examined by measuring the density of the mixture at different levels up to the pressure release opening. This can experimentally in a simple and reliable way be done by γ-ray attenuation. An example of the change of density versus time and level is shown in fig. 3 for the example of a vessel with 0,5 m hight and under the conditions of fast pressure release. The vessel was filled up to 2/3 with saturated liquid - refrigerant R 12 - before the release started.

After a boiling delay of a few tenths of a second the void - volumetric vapour content - is strongly rising in the part of the vessel which originally was occupied by pure liquid. The vapour dome is being filled partially with liquid during the violent flashing which can be seen from the decrease of the void from originally 1,0 to values between 0,4 and 0,7. After 1 to 2 s the influence of the flashing is reduced and a steady gradient for the density distribution is formed, resulting in a steadily increasing vapour content via the hight of the vessel and the fluid-dynamic behaviour finally is controlled by the phase separation to a large extent.

The temporal course of the pressure release as it is influenced by the foaming occurences is shown in fig. 4. This figure demonstrates the thermodynamic non-equilibrium effects between the phases. The experiments were made with the refrigerant R12 and the test vessel was filled up to 2/3 of its hight with this liquid before the expansion. By destroying a burst disk the pressure in the vessel was released from 20 bar to ambient pressure within 15 s. The pressure release was started at the moment B (fig. 4) and the very steep pressure gradient between B and C together with the experimental reading that during this period the liquid temperature is remarkably higher than the saturation temperature,

give the hint that there is a high boiling delay. This means that at the beginning only the vapour above the liquid level is expanding. Only at point C flashing evaporation and with this bubble formation starts in the liquid. In the period C - D the swell level of the liquid is moving upwards as explained ago due to bubble formation until it reaches the outlet opening of the vessel at point D leading to the release valve. By this the flow conditions in the valve ar changed at the time D because now a two-phase mixture is present there, whereas before gas was flowing containing only a few droplets as spray. The maximum velocity of the two-phase mixture is much lower than the sonic-velocity of pure vapour. In the vessel, however, at the same moment the thermodynamic disequilibrium is reduced powerfully and due to this the steam-production in the vessel during the period D - F is higher than the volumetric flow rate leaving the valve. As a consequence the pressure in the vessel is rising until point E at which moment the thermodynamic equilibrium between liquid and gas is reached. One can see this from the temperature-pressure-diagram. The increase of the pressure becomes slower in the period E - F until finally at point F the produced mass of vapour and the volumetric flow rate leaving the valve are in balance. From now on a steady pressure decrease can be observed showing at the time H a remarkable flattening of the pressure-time-curve. This can be explained by the fact that now the swell level is falling below the outlet opening of the vessel. Flashing, phase separation and the movement of the swell level can be calculated using physical models like that by Viecenz /1/. The mean volumetric flow rate moving in a two-phase mixture through the free surface into the vapour dome and separating from the liquid is depending on a large number of influencing parameters. Most papers in the literature /2-5/ are limited to an integral analysis where the volumetric flow rate of the gas or the vapour moving through the free surface of the swell level is deduced from experiments where gas is blown steadyly into stagnating liquid. The volumetric flow rate of the separating vapour usually is formulated as a function of the superficial velocity of the vapour flowing in the empty vessel and the results are given as mean values over the total volume of the mixture in terms of a mean void fraction. This procedure does not allow to take in account the radial and axial profiles of void fraction and velocity. The reason for this simplification in the literature is the lack of qualified measuring techniques for the local void fraction and the local phase velocities. A better procedure in developping an equation for phase separation is the drift flux model

by Zuber /6/ taking in account the velocity- and the density distribution. In this model the change of velocity versus the cross section and the hight of the vessel is taken in account. The vapour separation at the free surface is defined by

- geometrical parameters like diameter of the vessel, diameter of bubbles and height of the vessel
- hydrodynamic parameters, like superficial vapour velocity in the empty vessel, liquid velocity, movement of the phase boundaries and relative velocities between the phases
- thermodynamic parameters like latent heat of evaporation and densities of liquid and vapour and
- transport properties like viscosity of liquid and vapour.

The phase separation quantitatively can be described with the help of the void fraction and the drift flux between liquid and vapour. By combining the influencing parameters dimensionless numbers can be deduced for the void fraction and the drift flux velocity. These influencing dimensionless numbers can be also represented by ratios of forces, for example the inertia-, the gravity-, the viscosity- and the surface tension forces. In addition one has to take in account the effects of the bubble rising velocities in the liquid which are caused by axial and radial velocity profiles.

Based on the research in the literature /5/ and by using scaling laws Viecenz developed correlations for the void fraction and for the drift flux velocities which are shown in the fig. 5 and 6. In these figures also the calculated values are compared with experimental results.

The equation for the void fraction (fig. 5) is mainly determined by a modified Froude-number in which the superficial velocity of the vapour as characteristic velocity is used. This superficial velocity is the velocity of the vapour if it would flow in the empty vessel. In addition the diameter of the bubbles is choosen as another characteristic length and this bubble diameter is expressed by the Laplace-constant. At a Froude-number of 3 a change in the slope of the separation curve can be clearly seen, therefore the constant and the exponent with the Froude-number is changed at the fluiddynamic conditions, corresponding to a Froude-number 3. Other dimensionless numbers in the equation for the void fraction are the ratio between bubble- and vessel-diameter, the ratio of the densities and the ratio of the kinematic viscosities of liquid and vapour.

For describing the drift flux velocity similar parameters are used and also there the constant and the exponent have to be altered at a Froude-number of 3 (Fig.6).

The correlations in fig. 5 and 6 at first were developed for steady state flow conditions only. Using a computer program which predicts the time depending evaporation rate in the liquid, these correlations, however, are also good for calculating the transient behaviour of the void fraction and for the hight of the swell level in the vessel. Comparisons between calculated and experimental values of the swell levels showed good agreement /1/ (fig. 7).

3. Critical flow

In gases the travelling velocity of a pressure wave is equal to the maximum flow velocity at a super critical expansion in an orifice or in a convergent Venturi-nozzle. Gas-liquid mixtures have different travelling velocities in the gas bubbles and in the liquid bridges for the sonic waves. Because of the interaction between the phases which are caused by the momentum and shear stresses it would give no sense to assume that each of the phases is flowing with it's own sonic velocity in the outlet of the valve.

Local differences in pressure - versus the flow path of the expansion in the nozzle - effect that the gaseous phase because of its much lower density has a larger velocity than the liquid. The differences in the flow velocities between the phases - called slip - are limited and reduced by the friction and the momentum exchange. Therefore at first the question is rising up to which extent fluiddynamic equilibrium during the high acceleration in connection with the expansion in the valve can be reached. The high pressure drop in the nozzle is causing an additional flashing evaporation and boiling delay can produce thermodynamic disequilibrium and unstable conditions in the nozzle as shown already in fig. 4, where the pressure release and the flashing in the vessel were discussed.

The occurances in the nozzle are very difficult to measure and therefore theoretical models are to a large extent, based on assumptions concerning the thermodynamic equilibrium and the slip. These assumptions can only be checked with global experimental results, that is with the mass flow rate

or the pressure decrease versus time.

Limiting assumptions for the critical flow rate are on one side homogeneous flow, i.e. equal velocities of liquid and gas, with full thermodynamic equilibrium and on the other side fluiddynamic assumptions for a maximum slip ratio with thermodynamic disequilibrium, i.e. total boiling delay in the area of the nozzle or the orifice. Between this extreme any assumptions can be used, concerning the flow conditions in the gas and in the liquid as well as the evaporation rate. Theoretical models containing physically based assumptions for the velocity ratio between gas and liquid were elaborated for example by Moody /7/ as well as by Henry and Fauske /8/. The slip models are very simple formulated namely assuming that the slip is only a result of the accelerating pressure force along the flow path through the nozzle or the orifice. From this it results that the velocity ratio between gas and liquid is proportional to the 2. or 3. root of the density ratio between liquid and gas.

Equation (1) is the correlation developed by Henry /9/ for predicting the critical mass flow rate. In this equation the main influencing parameters are the void fraction, the slip, the compressibility of the gas and the densities of gas and liquid. Henry assumes that the slip, i.e. the velocity ratio between vapour and liquid is proportional to the root of the density ratio of both phases.

$$
\begin{aligned}
\dot{M}^2_{krit} = -\Bigg\{ s\Big[& [1+\dot{x}(s-1)]\dot{x}\,\frac{dv_D}{dP} + \{v_D[1+2\dot{x}(s-1)] \\
& + s\cdot v_D[2(\dot{x}-1)+s(1-2\dot{x})]\}\,\frac{d\dot{x}}{dP} + s[1+\dot{x}(s-2) \\
& - \dot{x}^2(s-1)]\,\frac{dv_{Fl}}{dP} + \dot{x}(1-\dot{x})\left(s v_{Fl} - \frac{v_D}{s}\right)\frac{ds}{dP}\Big]^{-1}\Bigg\}, \\
s = & \left[\varrho_D/\varrho_{Fl}\right]^{1/3}.
\end{aligned}
\tag{1}
$$

Fig. 8 shows as an example the difference in the results calculated with the different theoretical assumptions in comparison to measurements. In this example arbitrarily the pressure upflow of the nozzle was choosen as 35 bar and the void present before the flashing starts was varied between 0,05 and 0,25 . One can see that the theory according to Moody is predicting to high and the homogeneous equilibrium model to low mass flow rates for this example. Good agreement between measured and calculated data are

found by using the Henry/Fauske-model or the homogeneous disequilibrium model. This statement concerning the agreement between measurement and correlation can not be generalized. The agreement is depending from the initial pressure and from the void in front of the nozzle and there are areas in which the correlation according Moody or the homogeneous equilibrium model can give much better results with respect to the reality, then both other above mentioned models having here a more favourable position.

In our considerations concerning the critical mass flow, up to now, we had neglected the friction which plays an important role in a two-phase flow of high velocity. In short openings, like orifices or cracks or short nozzles this may be allowable. Long nozzles - i.e. with a L/D ratio larger 2 - cause besiedes pressure losses a redistribution of the flow pattern in the gas/liquid mixture, for example in the way that the originally homogeneous flow with equal phase distribution changes in an annular flow with liquid at the wall and gas in the center. By this the gas can flow faster and with less restrictions, however, it transports less momentum forces to the liquid. Due to its much higher density the liquid carries much more mass with it even if it flows slower than the gas or the vapour which is one reason why with increasing nozzle length the critical mass flow rate is decreasing as shown in fig. 9. The calculations and measurements in fig. 9 were performed for water of an original saturation pressure of 65 respectively 55 bar. For comparison in this figure also the critical mass flow rate is shown which would result if with isentropic expansion a homogeneous mixture with completely thermodynamic equilibrium would flow.

Most of the experiments and calculations dealing with critical mass flow of two-phase mixtures were performed for water in connection with the safety analysis for nuclear power stations. Purely hydrodynamic effects and phenomena like the acceleration due to depressurization or the momentum transport between the phases should be transferable to other substances including hydrocarbons if the thermodynamic and transport properties are wellknown. Much more difficulties arise, if thermodynamic effects, like the boiling delay, have to be valuated. For pure substances some data are available in the literature concerning the boiling delay. The situation, however, becomes rather complicated if one has to regard solutions with highly volatile components. Then the question rises whether the more volatile component goes immediately out of

solution when the depressurization starts and produces a high voidage in the nozzle which influences the flow remarkably or whether due to the slow mass transfer mechanism in the first moment of the depressurization the more volatile component is only forming a large number of small nuclei which, however, then may reduce the boiling delay of the liquid remarkably. The later assumption may be the more realistic one, and it is then interesting to what extent the critical mass flow rate is influenced by the concentration of nuclei.

Richter /10/ tried to take in account the influence of the number of nuclei to the critical mass flow rate by a theoretical analysis and he also compared his results with measured data. An example of his analysis is shown in fig. 10. One can see that depending from the assumed number of active nuclei and by this depending from the evaporation procedure, the result may vary from pure liquid flow through the nozzle to homogeneous conditions with complete thermodynamic equilibrium. The example in fig.10 was calculated with the assumption that at the entrance to the nozzle there is saturated water and the equations for the critical mass flow rate are based on separate balance equations for mass, energy and momentum for each of the two phases.

Calculations for solutions and mixtures in chemical plants need - as easily can be seen from the above deliberations - at first a detailed and reliable knowledge of the physical properties, then however, also the depressurization effects and the formation of nuclei must be wellknown which can be measured in relatively simple experiments. Based on the informations which were gained in the safety research work for nuclear power stations, well aimed experiments and theoretical analysis can be defind for substances and mixtures interesting in chemical engineering and from this computer programs for a reliable prediction of the depressurization in vessels of the chemical industry can be deduced.

4. Groups of apparatus and plants

Apparatus in the chemical industry and also in power stations usually form a compound and are highly mashed via a pipeline system such forming a plant. The neighbouring apparatus not always can be separated or isolated fast enough, if a vessel undergoes a blowdown so flow effects between the apparatus occur which make the calculation of a depressurization much more complicated.

In the analysis, one usually subdivides the plant or the group of apparatus in volumetric elements which are connected with each other by the balance equations for mass, energy and momentum.

$$\frac{\partial \varrho}{\partial t} + \nabla(\varrho \vec{v}) = 0,$$

$$\frac{\partial(\varrho h)}{\partial t} + \nabla(\varrho \vec{v} h) = -\nabla \vec{q},$$

$$\frac{\partial}{\partial t}(\varrho v) + \nabla(\varrho \vec{v} v) = -\nabla p + \nabla \pi \times \varrho g$$

These connecting points are called nodes. In each volumetric element, the hydro- and thermodynamic conditions and phenomena have to be known as good as possible or at least physical models have to exist which describe the phenomena good enough for a realistic result. Equations which describe the physical behaviour are called constituion equations whilest the balance equations are known as conservation laws. By defining these equations, one gets a very extensiv and usualle non-linear system of differential equations which can be subdivided in the two groups, mentioned above, namely constitution and conservation equations. The equations describing the physical phenomena - constitution equations - can be elaborated with the help of simple modeling experiments, at least in some cases. The solution of the system of differential equations has to be performed numerically which needs a large computer program. To check such a computer program with respect to the numerical procedure as well as to the physical relevance of the assumption made in the equations, large experimental set-ups - in the scale of pilot plants are necessary.

Since many years, so called integral - experimental plants, are available for nuclear safety research and in the tests there the computer programs for nuclear power stations are improved and assessed. In addition experiments in simpler designed and small test rigs were performed to look for special phenomena and with these experimental results constitution equations and physical assumptions in the computer programs could be improved too. In addition the numerical procedure was simplified aiming shorter calculation time and less need for storage in the computer. One of the largest integral test setups is operated in the USA at Idahofalls and is representing two primary loops of a pressurized water reactor, including its nuclear heating.

This setup is called Loss Of Fluid Test Facility (LOFT) /11/. Its main apparatus and components are shown in fig. 11. One can see from this figure, that it contains mainly the reactor pressure vessel, two steam generators, one of which containing only flow simulating components, pumps and the combining pipelines. During the depressurization the water/vapour-mixture is blown into a large vessel acting as a pressure suppression system and having a water reservoir in which the vapour blown in is almost completely condensed.

For the theoretical analysis and the comparison between calculated and measured results, this facility must be subdivided in volumetric elements and nodes which is demonstrated in fig. 12. The subdivision has to be performed very carefully which needs some experience to optimize the procedure because too many nodes increase the calculation time and the demand for storage in the computer and a too small number of nodes may falsify the results especially under the conditions of large pressure gradients.

The demand of computer time and need of storage is of course also depending on the equations specially the constitution equations, used in the program. From the numerical point of view, however, not always satisfying the theoretical scientists, simple empirical correlations have a great advantage which, however, have to be assessed and checked with respect to their reliability and validity in experiments, modeling at least a part of the real system.

Computer programs which were elaborated to describe the depressurization in nuclear power plants are shown in table 1. They are with exception of a view - CEFLASH, SATAN, and CRAFT originating in their basic concept from the submarine development - free available. However, they need large computers - for example Cyber 76 or IBM 360 - and their calculation time can be 10 - to 100 times longer than the real period of the depressurization. With new programs - TRAC /12/, RELAP V /13/, and DRUFAN /14/ - mainly two tendences of development can be seen. In large vessels the flow phenomena are two- and three-dimensionally described and under conditions where thermodynamic non-equilibrium is to be expected, equations and calculation procedures were developped, taking in account the transfer of energy, mass and momentum between the phases. Important physical phenomena are there the phase separation

and the critical mass flow rate out of the break or the relief valve.

Two examples shall demonstrate the reliability of predicting flow phenomena during depressurization with these programs and shall also make familiar with the influence of assumptions in the computer models. The most less sensitiv variable is generally the pressure, therefore this variable will not be discussed here. Much more difficult is to predict the mass flow rate and the density - respectively the void fraction - in the different nodes of the plant or the test facility.

Fig. 13 shows a comparison between experiment and calculation for a test in the LOFT-Facility. The calculation was done by the RELAP IV/MOD 5 computer program /15/. In this figure especially the influence of different assumptions onto the mass flow rate in the pipe line near the break location is demonstrated. The numbers in connection with the names of the physical models give the assumptions for the discharge coefficient of the flow at the break location which was of orifice like shape. From fig. 13, one however, can also see that the exact measurement of the mass flow rate is difficult because for the same experiment the reading of a Δp-orifice gives another value than that of a drag body. After the very first seconds of the blowdown the agreement between measured and calculated data is good.

More difficult is the prediction of the density because this variable is highly influenced by assumptions concerning the distribution of the vapour in the liquid and by evaporation effects. In fig. 14 a comparison between measurement and calculation is presented for another location of the piping system of the LOFT-Facility. There are two sets of calculated data shown, one is the so called pre-test prediction and the other one the post-test prediction. The pre-test prediction was performed before the experiments, with starting conditions for pressure, temperature and cross section of the break, defined before, which could not be fully varified in the experiment. Therefore these initial data were improved and are fully in agreement with the experiment in the post-test prediction. The theoretical models are the same in both predictions. The comparison shows that the vapour carries with it much less liquid in reality than the theoretical analysis predicts.

Comparing measured and calculated data, one however, has also carefully to check how good and exact the measuring techniques are and by this how one can rely on the measured results. This is especially important for experiments with temporarily fast changing two-phase mass flows. Usual mass flow meters like Prandtl - tubes or Pitot-tubes are not suitable for two-phase flows. Usually one uses momentum probes - so called drag bodys - and turbine meters, the signals of which are combined with the reading of a density measurement by γ-beam attenuation method trying to get a reliable information about the true mass flow. One of the simplest method measuring the temporal sequence of the mass flow rate, is to condense the vapour of the two-phase mixture in a vessel partially filled with subcooled liquid and by weighing or via the rising liquid level to determine the incoming mass flow rate. This is the case with the pressure suppression system of the LOFT-Facility. Drag bodys and turbine meters installed in the concourse leading to the pressure suppression vessel can then be calibrated also for non-steady conditions. Fig. 15 shows a comparison of the readings of different flow meters. One can see remarkable discrepances between the different measuring techniques and one realizes that none of the flow meters or combination of flow meters represents the real conditions exactly. A newer development for a measuring system to be used in non-steady two-phase flows, is the combination of a turbine meter, a drag body and a void meter as shown in fig. 16. For a correct reading the turbine needs as good as possible a homogeneous oncoming flow and therefore two sieves are placed in front of it. Measuring the void fraction with the γ-beam-attenuation method is certainly very reliable, however for many cases not fast enough even with γ sources of very high intensity. An electrical method measuring the impedance in concentrical annuli equally distributed over the flow cross section has the advantage of much less inertia, however, the disadvantage that this method has to be calibrated, which however, can be done under steady state conditions with the γ-beam attenuation method. This electrical measuring probe can be constructed with very small dimensions and therefore it is well suitable for local measurements. Large dimensions principally also make no difficulties, however, one has to take in account that the inertia of the turbine meter increases with its diameter and one also has take care that the centrifugal forces in the rotor do not become to high.

5. Scaling of modeling tests

Experimental and theoretical results with depressurization phenomena in apparatus and in plants are available in detail and to a reliable extent only for nuclear power plants up today and their informations are restricted to the fluid water. It is of great interest for the chemical engineer whether and up to what extent these experiences can be transferred to other substances especially to solutions and mixtures. Therefore the question raises whether modeling laws or existing and how good their predictions are.

It seems to be expedient to proceed in two steps discussing the scaling namely to perform modeling deliberations at first only for pure substances and then to think about solutions and mixtures. If and as far the physical phenomena are correctly described in the equations of the computer program then they should be also suitable for hydrocarbons or other non-organic substances supposed that the physical properties are wellknown. The question, however, is, how to deal with the thermodynamic or transport properties in the scaling laws because the depressurization usually covers a wide pressure range. These scaling deliberations then also define the planning of the modeling experiments. In this paper it is not possible to discuss the similarity theory in detail. A simple conception on scaling laws for these physical properties can be gained by assuming that all substances behave similar at the same reduced pressure - i.e. at the same ratio of the real system pressure to the critical pressure -. Plotting the properties - thermal, caloric and transport - versus the reduced pressure - one realizes that they differ over the whole pressure region only by a constant multiplier. Besides the fluiddynamic conditions the properties define the dimensionaless numbers like Reynolds-, Froude-, and Weber-number and it is therefore possible to take in account this constant factor of the properties in the modeling experiment by adjusting the fluiddynamic parameters like the velocity to get the same order of magnitude for these dimensionaless numbers in the model and in the original. By this one often succeeds to get the same conditions in the modeling experiment like in the original. An example for adjusting a modeling experiment performed with the refrigerant R 12 to the original water conditions is shown in fig. 17. In the original a large water loop consisting of evaporator, condenser and recirculation pump had to be compared with an other loop of the same components, however, operated with refrigerant R 12. In both loops blowdown experiments were performed. One can see from this

figure that mass flow rate, temporal depressurization and void fraction agree relatively well in both facilities.

More difficult conditions have to be expected if one wants to draw conclusions from the experimental experience done with pure substances to solutions and mixtures. Here is a great lack of knowledge concerning boiling delay, flashing evaporation, and mass transfer between the phases under the highly non-steady conditions. Therefore two groups of experiments should be recommended. The first one should deal with the thermodynamic behaviour during sudden depressurization and with special fluiddynamic conditions which are characteristic for apparatus and substance-combinations used in chemical industry. These tests could be performed in a small scale in laboratories of Universities and of course also at the industry. Besides this, however, also the interaction between the fundamental phenomena, like flashing in a vessel and critical flow in a leak with the system behaviour should be tested in pilot plants with not to small scale as integral test. Finally one should check to what extent the computer programs available in the literature and originally elaborated for nuclear power plants could be simplified and adjusted to the fluiddynamic conditions of chemical engineering plants. From these existing experiences and together with well defined and plant modeling experiments it should be possible to create reliable computer programs for predicting the depressurization in chemical plants without too great financial effort.

Fig. 1: Stable and unstable behaviour of vapour/liquid mixtures at pressure changes

Fig. 2: Schematic description of the hydro- and thermodynamic occurances during depressurization

Fig. 3: Temporal void distribution in different heights of a vessel and at the outlet nozzle.

Fig. 4: Thermodynamic non-equilibrium during depressurization of vapour/liquid mixtures (Refrigerant)

Fig. 5: Equation for the mean void fraction at phase separation, comparison of measurement and calculation

Fig. 6: Correlation for the drift flux velocity during phase separation, comparison measurement/calculation

Fig. 7: Mixture level during depressurization, comparison measurement/calculation O measured values, calculated values according: _____ separation model Viecenz, ------ Wilson, ... Zuber (C_{0rad}=1,0)

Fig. 8: Critical mass flow rate. Comparison of different correlations with a measurement (p_0 = 35 bar)

Fig. 9: Critical mass flow rate according to the two fluid model
Δ measured values by Sözzi and Sutherland, _____ theory, ---- homogeneous equilibrium model

Fig. 10: Influence of number of nuclei and nucleation onto the critical mass flow rate

Fig. 11: LOFT-facility primary loop with main components

Fig. 12: Nodalization in program RELAP 4 for LOFT-Facility
a steam generator, b pressurizer, c recirculation pump, d upper plenum, e core simulator, f simulator of steam generator, g break location, h pressure suppression system

Fig. 13a and b: Mass flow rate with depressurization (LOFT, cold leg)
a steam generator, b simulator of steam generator, c blowdown valve, d pressurizer, e recirculation pumps, f reactor pressure vessel, g pump simulator, h pressure suppression system, M measuring position

Fig. 14: LOFT L 1-4: Density in the broken loop, hot leg.

Fig. 15: Mass flow rate at the break position, comparison of different measuring techniques
● drag body with densitometer, Δ turbine with densitometer, □ drag body with turbine, ○ pressure difference measuring, pressure suppression vessel: ◐ liquid level, _____ RELAP-prediction

Fig. 16: Combination of measuring techniques for mass flow rate measurements in two-phase systems

Fig. 17: Experimental data during a blowdown (loss of coolant accident) comparison of tests performed in a water facility and in a R 12 loop.

Table 1: Computer programs for depressurization

Table 1: Computer programs for depressurization

free available

private owned

under development

Fußnote zu Seite 1:

* paper presented at the "Jahrestreffen der Verfahrens-Ingenieure, 1. - 3. October 1980 in Straßburg

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