THE USE OF DIERS METHODS FOR TWO-PHASE RELIEF OF VAPORISERS

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A convenient new method is presented for sizing vaporiser relief systems when two phase flow occurs initially. The use of this and other methods is discussed, and illustrated by reference to case studies.

VAPORISER TWO-PHASE RELIEF

INTRODUCTION

DIERS, the Design Institute for Emergency Relief Systems of the American Institute of Chemical Engineers, was formed in 1978. The 29 member companies, including ICI, funded research costing $1.6 million into sizing methods for two-phase relief of runaway reactors and vessels exposed to external heating. These methods are applicable to two phase relief of vaporisers.

Two types of vaporiser in common use are illustrated in figures 1 and 2. Under certain rare combinations of failures/maloperations (discussed in more detail below) it may be possible for a vaporiser to be isolated full of liquid with the heating on (see figure 3). In such a case, two-phase relief would occur, and, particularly if the relief set pressure equals the vessel design pressure, a much larger relief system would be needed than if the relief were vapour only. It is desirable, therefore, to be able to size the relief system accurately, so as to minimise oversizing and to keep the cost of the relief system itself and any downstream equipment (scrubbers, flares etc) as low as possible. A better choice of relief device set pressure may also lead to a smaller relief system size. This paper will describe how the methods developed by DIERS can be used for this purpose.

POSSIBLE CAUSES OF TWO PHASE RELIEF

For any given design of vaporiser installation, the possibility of the relief being two phase rather than vapour only should be considered during

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the Hazard Studies. In some cases it is possible to design out the problem. The situations given here are included as examples only, and are not intended to be an exhaustive list of all the possiblities.

1) The vaporiser could be correctly shut down and isolated empty, but if the liquid inlet valve were passing, it could gradually fill with liquid. If then, at start-up, a maloperation caused the heating to be turned on before the isolation valves were opened, then two phase relief would result. It should be remembered that, at start-up, it may be necessary to disable trips which would otherwise operate to stop the heating.

2) During normal operation, a sudden failure could cause loss of heating, eg steam failure, or heating fluid pump failure. If the liquid feed continued, the vaporiser might fill with liquid, and it might then be isolated, possibly by operation of trips. If the heating was then reinstated, two phase relief would occur.

A vaporiser normally operates with only a small proportion of its heat transfer area exposed to liquid (figures 1 and 2). The remainder of the heating surface vaporises droplets and provides superheat. Thus, if two phase relief occurs, a larger than normal heat transfer area is available for vaporisation, and the vaporisation rate is potentially much higher than normal. In order to alleviate this, consideration should be given to limiting the heating rate eg by a flow restrictor on the steam supply.

It is usual to arrange for the pressure of the liquid feeding a vaporiser to be less than the vaporiser relief pressure. This helps to minimise the number of relief events, since closing the vapour outlet valve will tend to blow liquid back down the liquid inlet line and cause vapour blanketing of the heat transfer surface. It also means that, even if the vaporiser is full enough for two phase relief to occur, there will be no additional feed of liquid to the vaporiser during relief.

PHYSICAL UNDERSTANDING OF TWO PHASE RELIEF

If a vaporiser is isolated, full of liquid, and the heating turned on, the liquid will first heat up to its boiling point at the relief set pressure. During this heating, a small amount of liquid will be relieved due to thermal expansion.

When the boiling point at the relief set pressure is reached, two-phase relief will begin. Vapour bubbles will be produced within the vaporiser, and these will displace saturated liquid into the relief system. This liquid will flash as it flows through the relief system.

Consider a case in which a margin is provided between the pressure at which the relief device will be first fully open (eg for a safety valve the set pressure plus 10%), and the maximum pressure allowable (the vessel design pressure plus 10% permitted accumulation). The minimum acceptable relief device size would cause the pressure to continue to rise following operation of the relief device, but to stop rising before the maximum pressure allowable has been exceeded.

During two phase relief, the vessel will progressively empty, and the fraction of vapour in the mixture entering the relief system will progressively increase. This means that heat removal from the vessel, which is largely due to latent heat, will also progressively increase as two-phase

venting continues. A point will be reached at which this heat removal rate equals the heat input rate. This is known as pressure "turnover", since the pressure will have reached a maximum and will fall thereafter. If the relief system is sized so that pressure turnover coincides with the maximum pressure allowable, it will be safe.

The above assumes that two-phase relief continues until the pressure turnover point is reached. However, it may be that the vaporiser disengages, ie begins to vent vapour only, instead of a two phase mixture, before the two-phase relief pressure turnover would have occurred. If so, the minimum vent size will be that for which vapour/liquid disengagement occurs just at the maximum vessel pressure allowable.

SIZING METHODS FOR TWO PHASE RELIEF

The following three methods are different approximations to the physical understanding described above. For each method, the vaporiser pressure versus time profile is illustrated in figure 4. All three methods assume that, during two-phase relief, there is a homogeneous vapour/liquid mixture in the vaporiser, and this homogeneous mixture enters the vent. This is a safe assumption; the fraction of vapour entering the vent may actually be higher than the average for the vessel.

All three methods are safe (when valid : the specified validity check must be made for method 3). The smallest of the vent sizes, given by those methods which are valid in a particular case, may be used.

1. Two-Phase Relief at Constant Pressure

This method neglects any emptying from the vaporiser whilst the pressure rises from that at which the relief device is first fully open, to the maximum pressure allowable. See curve 1 on figure 4. With this method, increasing the vaporiser design pressure will give a smaller required vent size. However, with this method, there is no reduction in calculated vent size if a relief system set pressure, lower than the design pressure, is specified.

Usually, the method will oversize the vent in cases where a margin is available between the set pressure and design pressure. (Although, in certain circumstances it may give a smaller vent size than method 2). The advantage of the method is that it is very quick to use, and, if it shows an existing vent to be adequate, there is no need to go further.

The relief system is sized to pass a volumetric rate of two phase mixture equal to the volumetric rate of vapour generation (less the small rate of reduction in liquid volume due to the vaporisation). The limiting condition for vent sizing is at the start of the venting process, when saturated liquid enters the vent. The vent area required is given by the following formula, in which all the parameters should be evaluated at the specified constant pressure, ie at the maximum vessel pressure allowable :

$$A = \frac{Q \quad v_{fg}}{h_{fg} \quad v_f \quad G}$$

In many cases, the two phase vent capacity per unit area can quickly and easily be calculated using the equilibrium rate model (1,2). For saturated liquid inlet conditions, this can be expressed as :

$$G = \frac{h_{fg}}{v_{fg}\sqrt{C\,T}}$$

Conditions of applicability for this method are:

- negligible friction, eg relief via a safety valve directly to atmosphere
- turbulent flow
- ideal physical properties (otherwise see ref 3)

2. Homogeneous two phase relief, taking advantage of overpressure

This method takes advantage of partial emptying of the vaporiser during two phase relief. It neglects the possibility of disengagement, ie two-phase relief reverting to vapour-only relief, before pressure turnover. See figure 4, curve 2.

As two phase relief proceeds, the vaporiser gradually empties of liquid. It is assumed that the vaporiser contents are homogeneous, ie that the mixture entering the relief system has the same vapour fraction as the average for the vessel. This vapour fraction increases with time as the vaporiser empties. A point is eventually reached when the heat input rate to the vaporiser is balanced by the heat removal with the venting fluid (effectively as latent heat). The pressure then turns over. If an adequate margin is provided between the relief system set pressure and the vaporiser design pressure, then it is possible to size the relief system so that the pressure turns over before the maximum vessel pressure allowable is exceeded.

Leung (4) derived the formula below, which allows a relief system to be sized for this case. The formula is an analytical solution to the differential heat and mass balances for the venting process. It assumes that the heat input rate, the relief capacity and all relevant physical properties are constant with pressure (and temperature) between the set pressure and the maximum pressure allowable. The vent size required has to be found by trial and error, ie by substituting the value of A, corresponding to different safety valve or disc sizes, into the formula, and selecting the valve/disc size which gives ΔT just less than that allowable.

$$\Delta T = \frac{Q}{GA\,C}\left[\ln\left(\frac{m_o}{V}\,\frac{Q}{GA}\,\frac{v_{fg}}{h_{fg}}\right) - 1\right] + \frac{V\,h_{fg}}{m_o\,C\,v_{fg}}$$

Average values of physical properties and of the heat input rate, between the vent opening pressure and the maximum pressure allowable, should be used. However, in order to arrive at a safe vent size, the vent capacity per unit area, G, should be evaluated at the pressure at which the vent is first fully open, ie at the set pressure plus 10% for a safety valve, or at the maximum bursting pressure of a disc including tolerances. Because the minimum value of G is used, the method tends to become increasingly conservative as the overpressure, ie the margin between the set pressure and the maximum pressure allowable, increases.

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This method will usually give significantly smaller vent sizes than method 1 (the exception being when the heat input rate at the maximum pressure allowable is very low : in such cases, the use of an average heat input rate can make method 2 oversize excessively). Method 2 is fairly quick and easy to evaluate and needs little more data than method 1.

3. Two phase relief, taking advantage of disengagement

This method allows account to be taken of vapour-liquid disengagement. The method is only valid in cases where disengagement occurs before pressure turnover would have occurred anyway.

When a liquid boils, vapour bubbles are produced which rise through the liquid and disengage at the surface. The presence of bubbles within the liquid causes the level to rise or "swell" (see figure 5). In a relief situation, if the liquid level rises as far as the inlet to the relief device, then two phase rather than vapour relief occurs. Methods for estimating the extent of the level swell in a given situation were developed by DIERS (5,6). These methods are only applicable if the fluid does not exhibit surface-active foaming behaviour. Trace quantities of certain substances can give rise to surface-active properties, and for reactor relief, DIERS recommend that the safe assumption of homogeneous two phase venting should always be made (7). However, in the case of vaporisers, it is usually reasonable to assume that the material vaporised is not surface-active, since, if it were, the vaporiser would fill with foam during normal operation and would not work.

As the vaporiser relieves, it progressively empties itself of liquid. A point will be reached at which two phase venting stops and vapour-only venting begins. The quantity of liquid remaining in the vaporiser at this point can be estimated using the DIERS level swell methods. These methods require the definition of the flow regime in the vaporiser during relief; this tends to be droplet, or occasionally churn-turbulent. The level swell methods are not applicable in the case of some bayonet type vaporisers which have horizontal baffles in the superheat section.

In order to take advantage of vapour-liquid disengagement in relief system sizing, it is necessary to provide a margin between the relief set pressure and the design pressure of the equipment. The relief system can then be sized so that the pressure rises during the initial two phase relief, but the vaporiser empties sufficiently for relief to become vapour only before the maximum pressure allowable has been exceeded (see curve 3 of figure 4). Once vapour only venting begins, the vaporiser pressure rapidly drops since the vent size will be much bigger than is needed for vapour-only relief.

To calculate the required vent size, it is first necessary to calculate α, the vessel void fraction at which vapour/liquid disengagement first occurs, using DIERS methods (5,6). α should be evaluated at conditions corresponding to the maximum pressure allowable. The vent size may then be calculated using the formula below, which always yields a vent area which is smaller than or equal to that calculated for homogeneous two phase venting using method 2 above. It is only valid when disengagement occurs before pressure turnover would have occurred anyway. Hence it is essential to follow the calculation of vent area by a validity check as defined below. Subject to the validity check, the following formula, derived in the Appendix, can be used to size the relief system:

$$A = \frac{Q \ \ln\left((1-\alpha_0)/(1-\alpha)\right)}{G\left[\dfrac{h_{fg}\, v_f \ (\alpha-\alpha_0)}{v_{fg}(1-\alpha_0)\ (1-\alpha)} + C\,\Delta T\right]}$$

In the above formula, average values of the heat input rate, Q, and of physical properties, between the vent opening pressure and the maximum pressure allowable should be used. The following criterion of validity should be applied, after the required vent area, A, has been calculated using the above equation :

$$Q_m > \frac{GA \ \ h_{fg}\, v_f}{v_{fg}\,(1-\alpha)}$$

The method makes the safe assumption of homogeneous two phase venting until disengagement occurs; no account is taken of the fact that the two phase mixture entering the vent may have a higher vapour fraction than the average for the vessel. It is recommended that the initial value, ie at the vent opening pressure, be used for the vent capacity per unit area, G. This will however tend to make the calculated vent area increasingly conservative at high allowable overpressures.

When valid, method 3 is the most accurate of the three methods, and will give the smallest vent size. However, it is more time-consuming to evaluate and needs considerably more data than the other methods. (For example, a detailed drawing of the vaporiser will usually be needed, and this may not be available until relatively late in the project. In some cases, the geometry of the vaporiser internals is such that a level swell calculation cannot be done, and so method 3 is inapplicable.) Method 3 should therefore be evaluated last of the three methods. If methods 1 or 2 give acceptable vent sizes, then method 3 may not be necessary.

EXAMPLES

The following examples illustrate the behaviour of the design methods which have been described.

Example 1

A new bayonet type vaporiser was to be installed. There was a minimum set pressure for the relief system of 25 bara, governed by the required operating pressure, but since the vaporiser was to be new, there was the option of specifying a design pressure above 25 bara, and/or of specifying a design without horizontal baffles, if this would significantly reduce the cost of the relief system. It was not possible to restrict the steam supply to the vaporiser, because, in normal operation, the pressure drop over such a restrictor would tend to reduce the steam temperature at the vaporiser, and this would increase the size of vaporiser required.

The fluid being vaporised was toxic. For this reason it was desirable to minimise both the quantity and flowrate relieved to a scrubber system. A safety valve system was preferred to a bursting disc system because the

valve would reseat and because the possibility of spurious failure of a bursting disc was considered unacceptable.

The safety valve size required was calculated for a number of possible vaporiser design pressures using each of the sizing methods. The size required for vapour-only relief was also calculated for comparison. The results are given in table 1.

In table 1, the stated "overpressure" corresponds to the difference between the pressure at which the safety valve was first fully open (gauge set pressure plus 10%) and the maximum vessel pressure allowable (gauge design pressure plus 10%). (Note that this overpressure is irrelevant for vapour-only venting and for method 1. For these two methods, the vent sizes given in Table 1 would still apply if the set pressure were equal to the design pressure.) The valve sizes given are the API orifice size (ref 8), letters D (smallest area) to Q (largest area), together with the corresponding inlet and outlet pipe diameters for the valve.

It can be seen that the valve sizes required for two phase relief are considerably larger than are needed for vapour only relief. For two phase relief, the safety valve size required can be greatly reduced by allowing a margin between the set pressure and the design pressure, and vent sizes become gradually smaller as this margin is increased.

At 30 bara design pressure, method 2, homogeneous two phase relief, gave the minimum required vent size. Method 3, taking account of disengagement, was invalid. The reason for this was that the superficial vapour velocity in the vaporiser was only slightly lower than the terminal velocity of the liquid droplets, and disengagement was not predicted until the vaporiser was nearly empty, ie well after the pressure had turned over.

TABLE 1
SUMMARY OF CALCULATED SAFETY VALVE SIZES FOR EXAMPLE 1

Design P bara	"Over P" % gauge set pressure	Vent size required: Vapour only	Two phase venting: Method 1	Two phase venting: Method 2	Two phase venting: Method 3
25	0	F 1.5"x2"	Q 6"x8"	Q 6"x8"	Invalid
30	22.9	E 1" x2"	N 4"x6"	L 3"x4"	Invalid
35	45.8	D 1" x2"	K 3"x4"	J 2"x3"	J 2"x3"
38	59.6	D 1" x2"	G 1.5"x2.5"	H 1.5"x3"	G 1.5"x2.5"

Because the steam supply was not restricted, the heat input rate to the vaporiser was limited only by the heat transfer capacity. Increasing the design pressure increases the saturation temperature at the design pressure and so reduces the temperature driving force for heat transfer and the heat input rate. At 35 bara, both methods 2 and 3 gave the same size safety valve, which was smaller than that obtained using method 1. The superficial vapour velocity at the maximum pressure allowable was reduced from that at 30 bara design pressure. Disengagement was predicted when the void fraction, α , within the vaporiser reached 0.66.

At 38 bara design pressure, the heat input rate at the maximum pressure allowable was very low. For this reason, method 1, which depends only on conditions at the maximum pressure allowable, gave a small vent size. Method 2, using the average heat input rate between the vent opening pressure and the maximum pressure allowable, gave the biggest vent size. Method 3 gave the same small valve size as method 1, with a slightly smaller required vent area. The void fraction for disengagement depends on the heat input rate at the maximum pressure allowable, and was calculated as 0.33.

Example 2

In this case, a safety valve was to be sized for an existing bayonet type vaporiser (which did not contain horizontal baffles). It was possible to restrict the steam supply to a flowrate equivalent to 180 kW heat input rate. At this heat input rate, the vaporiser was somewhat oversized for the required duty. The vaporiser had a design pressure of 25 bara, and it was decided that the relief system set pressure could be reduced to 21.7 bara if necessary. The vent sizes given in Table 2 were obtained.

Again, two phase relief requires much larger vent sizes than vapour only relief. Of the two phase vent sizing methods, method 3, allowing for disengagement, gave the smallest vent size. Both methods 2 and 3 gave substantial reductions in vent size over method 1.

TABLE 2
SUMMARY OF CALCULATED VENT SIZES FOR EXAMPLE 2

Design P bara	"Over P" % gauge set pressure	Vent size required			
		Vapour only	Two phase venting		
			Method 1	Method 2	Method 3
25	17.5	E 1"x2"	L 4"x6"	J 2"x3"	H 1.5"x 3"

It should perhaps be noted that method 3 gave a smaller vent size than method 2 only because the vaporiser was oversized. This reduced the vapour superficial velocity, with the result that disengagement occurred at a void fraction of only 0.25. If the smallest size of vaporiser which could achieve the required vaporisation rate had been used, then method 3 would have been found invalid, and so method 2 would have yielded the smallest vent size. Jacketted pipe vaporisers (figure 2) tend to operate at higher vapour velocities than bayonet type vaporisers, and so it is less likely than for bayonet vaporisers that method 3 will give a smaller vent size than method 2.

CONCLUSIONS

Methods have been presented which allow the sizing of vaporiser relief systems when two phase flow is expected. A larger relief system size is needed for two phase relief than for vapour only relief.

When two-phase relief is expected, it is usually advantageous to provide a margin between the relief device set pressure and the vaporiser design pressure.

Of the three two-phase relief sizing methods presented (all of which are safe, when applicable), each may sometimes yield the smallest vent size. Method 2 usually gives the smallest vent size. If the heat input rate at the maximum pressure allowable is low compared with that at the relief device opening pressure, then method 1 may give the smallest size. If the vapour superficial velocity at the maximum pressure allowable is low (below about 0.1 m/s) then method 3 may be valid, and so give the smallest size.

NOMENCLATURE

A vent area (m2)

C liquid specific heat capacity (J/kg K)

G vent system capacity per unit area (kg/m2 s)

h_{fg} latent heat of vaporisation (J/kg)

m mass of liquid in vaporiser (kg)

m_o mass of liquid initially in vaporiser (kg)

Q heat input rate (W)

Q_m heat input rate at the maximum pressure allowable (W)

t time (s)

T temperature within vaporiser (K)

ΔT temperature difference between pressure at which vent is first fully open and that at the maximum pressure allowable (K)

v_f specific volume of liquid (m3/kg)

v_{fg} difference in specific volume between vapour and liquid phases (m3/kg)

V vaporiser volume (m3)

α void fraction within vaporiser at the point of vapour/liquid disengagement = (vapour volume)/(total volume)

α_o initial void fraction within vaporiser

ρ_f liquid density (kg/m3)

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FIGURE 1

BAYONET TYPE VAPORISER : NORMAL OPERATION

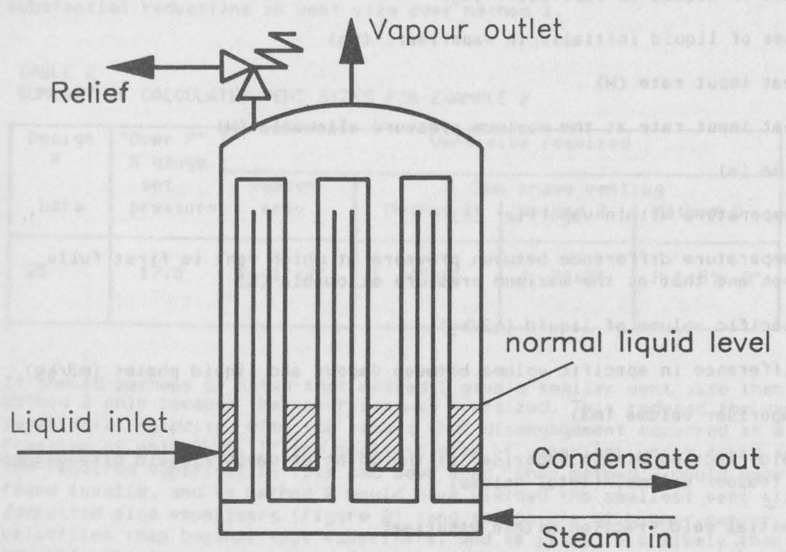


FIGURE 2

JACKETTED PIPE VAPORISER : NORMAL OPERATION

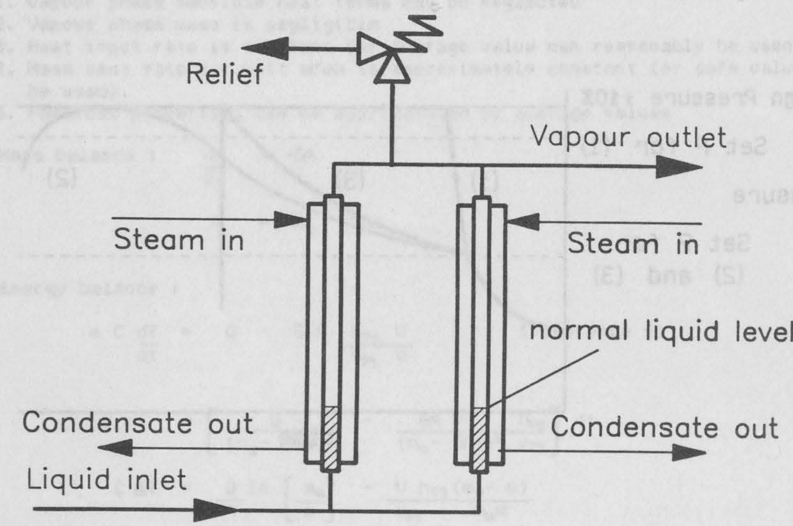


FIGURE 3

TWO-PHASE RELIEF SITUATION

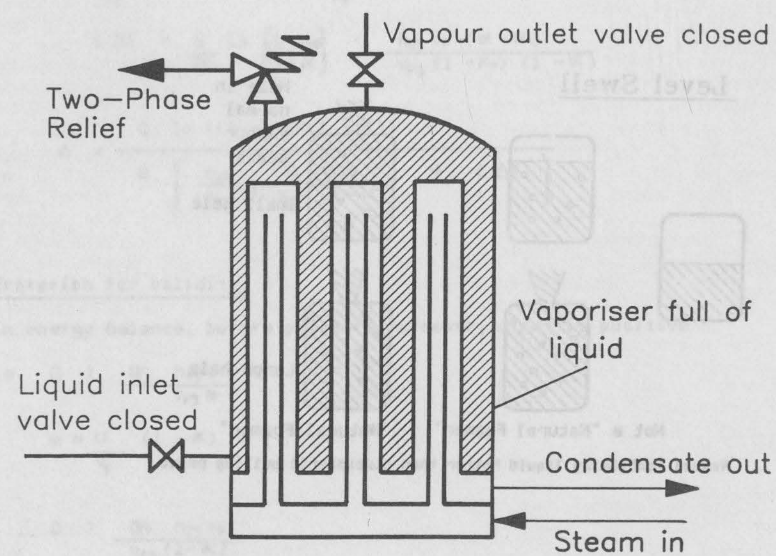


FIGURE 4

PRESSURE VERSUS TIME PLOTS FOR THE THREE SIZING METHODS

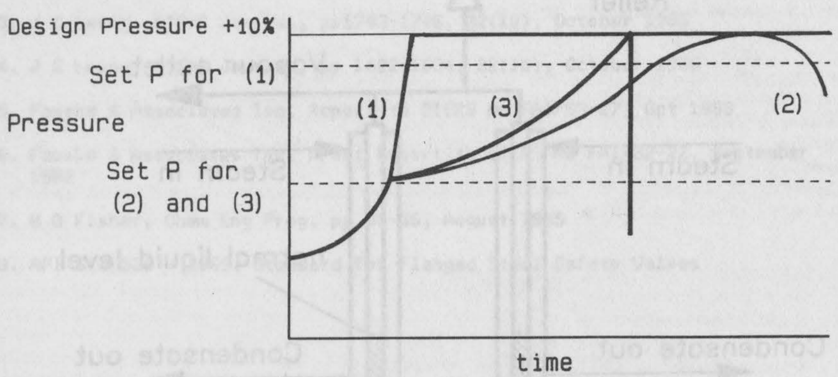
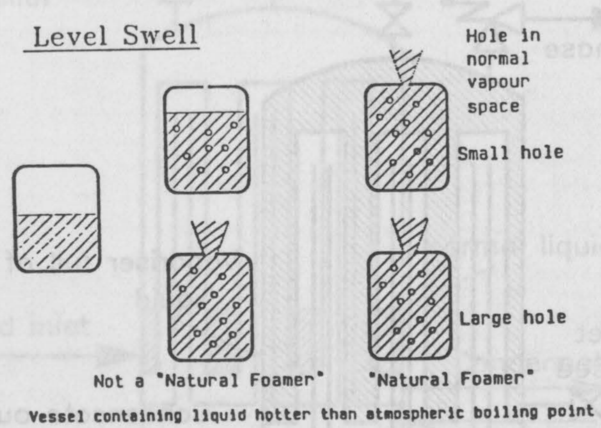


FIGURE 5



APPENDIX : DERIVATION OF METHOD 3 FORMULA

Assumptions :

1. Vapour phase sensible heat terms may be neglected
2. Vapour phase mass is negligible
3. Heat input rate is constant (or average value can reasonably be used).
4. Mass vent rate per unit area is approximately constant (or safe value can be used).
5. Physical properties can be approximated by average values

Mass balance : $\frac{dm}{dt} = -GA$

$$m = m_o - GAt$$

Energy balance :

$$m\,C\,\frac{dT}{dt} = Q - G\,A\,\frac{h_{fg}}{v_{fg}}\frac{V}{m} \qquad \text{(reference 4)}$$

$$\therefore C\,dT = \left[\frac{Q}{(m_o - GAt)} - \frac{GA\,V}{(m_o - GAt)^2}\frac{h_{fg}}{v_{fg}}\right]dt$$

$$\therefore C\,\Delta T = \frac{Q}{GA}\ln\left[\frac{m_o}{m}\right] - \frac{V\,h_{fg}\,(m_o - m)}{v_{fg}\,m_o m}$$

but $m = \frac{V}{v_f}(1-\alpha)$; $m_o = \frac{V}{v_f}(1-\alpha_o)$ (see assumption 2)

$$\therefore C\,\Delta T = \frac{Q}{GA}\ln\left[\frac{1-\alpha_o}{1-\alpha}\right] - \frac{h_{fg}\,v_f\,(\alpha-\alpha_o)}{v_{fg}\,(1-\alpha_o)\,(1-\alpha)}$$

$$\therefore A = \frac{Q\,\ln((1-\alpha_o)/(1-\alpha))}{G\left[\frac{h_{fg}\,v_f\,(\alpha-\alpha_o)}{v_{fg}\,(1-\alpha_o)\,(1-\alpha)} + C\,\Delta T\right]}$$

Criterion for validity

In energy balance, before pressure turnover, dT/dt is positive

ie $Q > \frac{GA\,h_{fg}\,V}{v_{fg}\,m}$

$$m = \frac{V}{v_f}(1-\alpha)$$

$$\therefore Q > \frac{GA\,h_{fg}\,v_f}{v_{fg}\,(1-\alpha)}$$