EMERGENCY RELIEF STREAM DISPOSAL USING JET CONDENSERS

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The disposal of emergency relief streams following runaway chemical reactions usually involves a dump tank to knock out the liquid flow, followed by a quench tank to remove the remaining condensable gas or vapour. Such quench tanks have traditionally used sparge pipes to condense the gas or vapour. Recent research has shown that jet condensers provide an effective alternative solution to this problem. The paper reviews recent experimental results obtained during research into the use of jet condensers for quench tanks and provides the basic equations for the design of quench tanks using these jet condensers. The new methodology developed here adds confidence to the design of quench tanks and often results in smaller quench tank volumes than would be required when using traditional sparge pipes.

Key words: runaway reactions, venting, emergency relief, disposal, containment, quenching, jet condensers

INTRODUCTION

Increased safety, health and environment considerations, including tighter regulatory controls, are rapidly restricting the previously established practice of a direct release to the atmosphere for chemical reactor relief streams. The correct design of disposal systems is therefore becoming more important, both to ensure their operational efficiency to meet emission standards and to minimise expensive overdesign.

A great deal of research has been and still is being undertaken into the design of emergency relief systems for the relief of runaway chemical reactors [1]. This research has concentrated on the design of adequate vent sizes for pressure relief. In contrast, little research work has been carried out on containment and disposal systems for the chemical process industry.

API RP 521 [2] contains some guidance and recommendations for the design of horizontal knock-out drums and catchtanks, however there is little information available in the open literature on the design of quench tanks for chemical relief streams. Keiter [3] has described the design of a non-vented quench tank using a sparge pipe which contains some general recommendations on the design of quench tanks. These, together with recommendations by Grossel [4] and Fauske [5], lead to the following 'rules of thumb' for the design of quench tanks:

- determine the maximum allowable temperature in the quench tank; this depends on the maximum allowable vapour pressure, typically it corresponds to a final temperature which should be 10 K below the boiling point of the mixture
- calculate minimum required quench liquid volume using a simple, ideal heat balance
- determine the required quench tank volume; the recommendation is that the final fill level should not exceed 90 % in order to allow for a freeboard volume for non-condensable gases of a minimum of 10 %.

For the design of a sparge pipe:

- the recommended hole diameter is 1/8 - 3/8 inches (3 - 10 mm); if required, a hole diameter of up to 2 inches (50 mm) may be used without violent water-hammer effects
- the total hole area should be 1.0 to 1.5 times the vent line cross-section

- it is recommended that a T-shaped quencher arm is used with several rows of holes on the opposite sides in order to minimise reaction forces and improve mixing
- a centre-to-centre spacing of greater than three hole diameters is recommended.

The above 'design guide' includes a fair number of assumptions and uncertainties, the main ones being:

- complete condensation of the relief stream vapour; no consideration is given to maximum allowable freeboard gas velocity
- thermodynamic equilibrium, impliing very fast heat and mass transfer
- an even vapour distribution in the quench liquid
- in general terms it is known that significant quantities of non-condensable gases will reduce the disposal efficiency, however there is no quantification of the effect and no design guidance for different scenarios

A design using these recommendations results in a quench tank size which is typically two or three times the reactor volume.

In view of the above, research work was started a few years ago in Germany to evaluate the characteristics of different disposal systems in order to develop a more rigorous design methodology. This would also allow the disposal efficiency of a system to be quantified with a reasonable degree of confidence.

The overall objective of the research program was to improve/optimise current disposal system design practice with the following ultimate aims:

- high disposal efficiency for both liquid and gas, even in the presence of non-condensables in the relief stream
- ideally no limitations on availability, the disposal system should preferably operate without external energy
- wide applicability, i.e. to different vessels/reactors, chemicals and multi-purpose plants
- minimum plant space requirements, allowing 'add on' installation to existing plants
- minimum cost (emergency disposal systems are additional fixed cost equipment not used under normal process conditions)
- few design constraints, i.e. quench tank dimensions should be determined by minimum required quench liquid not by restrictions with respect to geometry, maximum gas flow rate, etc.

Research was carried out on cyclone separators by Ruppert *et al* [6,7] and quench tanks, the latter using both traditional sparge pipes (Beher [8]) and the novel use of jet condensers (Hermann [10] and Hafkesbrink and Schecker [11-14]) to effect condensation of the relief stream.

This paper reviews the research on disposal of emergency relief streams using jet condensers and presents the basic equations for the design of quench tanks using such condensers. The advantages and limitations of the use of jet condensers are discussed.

JET CONDENSER CHARACTERISTICS

Jet condensers, perhaps better known as steam injectors or ejectors are standard equipment, usually used for liquid pumping or heating by direct contact heat transfer. They have been called jet condensers in order to emphasize the different objective of their use in this application i.e. condensation rather than pumping or heating. Their operating principle can be explained with reference to Figure 1. Pressurized vapour is expanded in the vapour expansion nozzle resulting in the transfer of pressure energy into kinetic energy. This usually produces a sonic flow in the nozzle. Liquid is entrained by the transfer of kinetic energy from the gas or vapour phase to the liquid phase. Jet condensers operate without external energy and are therefore ideal for use in emergency relief systems.

A highly turbulent flow of both vapour and liquid is produced in the mixing nozzle with liquid mass flow rates of 30 to 100 times greater than that of the vapour or gas. This ensures intensive heat and mass transfer resulting in effective condensation which is almost complete at the end of the mixing nozzle.

RESEARCH RESULTS

The research, carried out on a pilot plant with a reactor of 250 l discharging into a quench tank of 1 m^3, showed that jet condensers could be used over a wide range of operating conditions with little effect on their condensation efficiency from changes in pressure, temperature or quantity of non-condensables in the vapour stream [9-14].

In practice, jet condensers can be installed either inside the quench tank or fitted externally (see Figure 2). Internal installation is however usually preferred for simplicity and to minimize the pipe work required.

The standard nozzle diameters for jet condensers of 7 to 41 mm (ca. 1/4 to 1 5/8 inches) are similar to sparger pipes. The risk of blockages by viscous products should therefore be the same or possibly less due to ideally shaped nozzles, however this assumption has still to be validated experimentally.

Flow Characteristics

A detailed examination was made of the flow characteristics through the jet condenser under conditions typical of those found during emergency relief situations. Typical results are shown in Figure 3 and Figure 4. It was found that the coolant flow rate is always several times the minimum flow rate required for complete condensation as calculated from the heat balance.

The minimum operating overpressure is ca. 10 kPa above the hydrostatic backpressure of the system and the research showed that as soon as this pressure is exceeded, jet condensers start to operate efficiently.

Although it was found that the presence of non-condensables in the vapour stream reduces the liquid coolant flow rate the liquid flow rate still exceeds the minimum required for complete condensation and, even with a gas stream containing 100% non-condensable, the resulting liquid flow rate is still sufficient for effective heat transfer.

Disposal Efficiency

The actual disposal or condensation efficiency of a quench tank using a jet condenser was found to depend on the final subcooling available, (i.e. the temperature difference between the boiling point of the mixture and its final temperature), the corresponding vapour pressure and also on the quantity of non-condensables in the vapour stream.

A sufficient coolant flow rate is essential for a high condensation efficiency. This is always the case as long as the subcooling is not too low. There is a minimum subcooling at which the coolant flow almost stops and vapour breaks through nearly uncondensed. This so-called break-through subcooling corresponds to a distinct increase of the volumetric flow rate leaving the quench tank, i.e. the exit flow rate (see Figure 5). However, this break-through occurs at a subcooling significantly below 10 K (see Figure 6). This has been experimentally validated for different systems of vapour and quench liquid [12,13]. The break-through subcooling gives a limitation for the use of jet condensers. It is recommended for design purpose to use a final subcooling of 10 K minimum in order to ensure that the break-through point is not reached.

If a minimum subcooling of 10 K is used, which usually corresponds to a vapour pressure of ca. 20 kPa, the total condensation efficiency, on a weight basis, derived from the overall mass balance for the released vapour, will generally be greater than 99 % without non-condensables present and ca. 95 % when there is 10 % of non-condensables [10].

The condensation efficiency at any instant is the differential of the total condensation efficiency and therefore changes during the relief period (see Figure 7). As long as the subcooling is not less than 20 K the condensation efficiency obtained is equal to that predicted assuming that there is always complete condensation and thermodynamic equilibrium between liquid and gas phase. If the subcooling is less than 20 K a deviation from the thermodynamic equilibrium is found. However, as this occurs only at the end of the relief period and thermodynamic equilibrium occurs for most of this period, there is only a slight effect on the total condensation efficiency.

A theoretical model, derived from the equations of state for heat, mass and momentum, has been presented in [13]. It takes account of the thermodynamic non-equilibrium at a low subcooling and can also be used to calculate the actual condensation efficiency (see Figure 8). In practice the actual condensation efficiency will be slightly higher than the theoretical one.

Both, the thermodynamic equilibrium model and the theoretical model, provide a useful basis for the design of quench tanks using jet condensers. It is recommended to use the thermodynamic equilibrium model to predict the condensation efficiency at subcooling values of greater than 20 K. If the subcooling is less than 20 K the thermodynamic equilibrium model provides the upper limit and the theoretical model the lower limit of the condensation efficiency.

The research [9-14] has shown that jet condensers are ideal for use in quench tanks and such a system would possess many of the 'ideal' characteristics of disposal system design outlined above. They operate without external energy and have very high heat and mass transfer rates (due to high turbulent flow of vapour and liquid), resulting in the optimal use of coolant thermal capacity because of the intensive circulation. This results in very few constraints on the quench tank design.

DESIGN METHODOLOGY

For the condensation of a single phase all vapour flow, the basic design equation is the total heat balance. However the equation must be modified if liquid or non-condensable gas is present. Since the research has shown that it is a valid assumption that total heat transfer and thermodynamic equilibrium occurs in jet condensers, equation (1) can be used to calculate the minimum quantity of quench fluid required.

$$m_{Vap} \cdot \left[c_p\left(T_{Vap,init} - T_{final}\right) + \Delta h_v\right] = m_{W,min} \cdot c_{p,W} \cdot \left(T_{final} - T_{W,init}\right) \tag{1}$$

In order to use this equation, the initial quench fluid temperature must be determined bearing in mind the ambient conditions surrounding the quench tank. As stated above it is preferable to choose a final temperature 10 K or more below the boiling point of the final mixture in the quench tank. Complete condensation can be assumed under such conditions. The heat capacity of the quench tank walls and other heat losses through the walls can be neglected, as authors' experience has shown that these are less than ca. 1 % of total heat released [15].

The minimum quench tank volume required for a vented system can then be simply calculated from the mass and densities of the quench fluid and incoming vapour:

$$V_{min} = \frac{m_{W,min}}{\rho_{l,W}} + \frac{m_{Vap}}{\rho_{l,Vap}} \tag{2}$$

For a non-vented quench tank the calculations must also consider gas space compression due to liquid level swell and temperature rise as described by [3].

Provided there is no foam formation, it is recommended that the quench tank volume final fill level should not exceed 90 % (this applies only for small quantities of non-condensable gases, for large quantities at the end of the relief period, which is a rare case, the final fill level should be reduced respectively).

$$V = \frac{V_{min}}{r} \tag{3}$$

where r is the final fill ratio (i.e. usually r = 0.9).

Calculation of Condensation Efficiency

Step 1: calculate gas flow rate leaving quench tank

The gas flow rate due to replacement of gas by condensed vapour and the rise in temperature based on ideal gas law and a constant pressure can be calculated from:

$$\dot{V}_{gas} = \frac{\dot{m}_{Vap}}{\rho_{l,Vap}} + \frac{V_{gas,init}}{T_{gas,init}} \frac{dT}{dt} \tag{4}$$

Step 2: estimation of vapour concentration in the gas space

Assuming that thermodynamic equilibrium exists between the quench liquid and the gas space the vapour concentration in the gas space is:

$$y_{Vap} = \frac{p_{Vap}}{p} \tag{5}$$

where p_{Vap} is the saturated vapour pressure above the liquid. The estimation of the vapour pressure depends on the mixture properties and whether the condensate is soluble or non-soluble in the quench liquid.

Step 3: estimation of non-condensed vapour flow rate

Based on ideal gas law and constant pressure in the quench tank the non-condensed vapour flow rate is

$$\dot{m}_{Vap,non\text{-}cond.} = \frac{p \cdot \dot{V}_{gas}}{RT} \cdot y_{Vap} \cdot M_{Vap} \tag{6}$$

Step 4: calculation of condensation efficiency

The condensation efficiency can now be calculated from:

$$C_{eff} = 1 - \frac{\int_0^t \dot{m}_{Vap,non\text{-}cond.}\, dt}{m_{Vap}} \tag{7}$$

The calculation should be done stepwise in order to take into account changes in flow rates, temperature, vapour pressure etc. with time. For a constant vapour flow rate (before quenching) calculation intervals of 5 K with respect to. the temperature rise of the quench liquid are usually sufficient.

Flow Calculations

Step 1: calculate critical pressure ratio for the vapour in question:

$$\varepsilon_{crit} = \left[\frac{2}{\kappa+1}\right]^{\frac{\kappa}{\kappa-1}} \tag{8}$$

Step 2: compare design pressure ratio to critical pressure ratio:

$$\varepsilon = \frac{p_{down}}{p_{up}} \tag{9}$$

where p_{down} is the jet condenser outlet pressure, i.e. hydrostatic back pressure, and p_{up} is the jet condenser inlet pressure.

Step 3: calculate vapour mass flux using either equation (10) for subsonic flow or equation (11) for sonic or choked flow

for subsonic flow:

$$\dot{w} = C_F \cdot \frac{p_{up}}{\sqrt{\frac{R\,T_{up}}{M}}} \cdot \varepsilon^{1/\kappa} \cdot \sqrt{\left(1 - \varepsilon^{\frac{\kappa-1}{\kappa}}\right) \cdot \frac{2\kappa}{\kappa - 1}} \tag{10}$$

for sonic flow:

$$\dot{w} = C_F \cdot \frac{p_{up}}{\sqrt{\frac{R\,T_{up}}{M}}} \cdot \sqrt{\kappa \cdot \left[\frac{2}{\kappa + 1}\right]^{\frac{\kappa+1}{\kappa-1}}} \tag{11}$$

using a contraction coefficient $C_F = 0.97$ for nozzles.

Step 4: determine required total jet condenser cross section:

$$A = \frac{\dot{m}_{vap}}{\dot{w}} \tag{12}$$

Pipe flow calculations may be required in order to determine the jet condenser inlet pressure. The effect of a jet condenser disposal system on the required relief area can be considered as follows. Generally, if the total jet condenser cross sectional area is two times the relief device area or larger, the vapour mass flow rate is not adversely affected by the jet condensers. In this case the mass flow rate is determined only by the relief device. Otherwise the flow rate may be limited by the jet condenser cross sectional area. It is of course also possible to design an emergency relief system based on the total jet condenser cross sectional area.

Step 5: choose number and type of standard jet condensers

The number and type of standard jet condensers are simply chosen such that their total cross sectional area is equal or greater than the required total jet condenser cross sectional area.

An internal installation is preferred as explained above. A "star arrangement" (see Figure 9) should be used with no more than 8 jet condensers at each level. Several levels are possible (see Figure 10). The top level should be 0.5 m below the liquid surface.

Additional Design Aspects

At the end of the relief stream flow vapour above the quench fluid will diffuse into the atmosphere as in any open system. This diffusion is not included in the calculation of the condensation efficiency.

The reaction forces are mainly dependent on the operating pressure and should be considered for each specific situation.

It is recommended that an anti-vacuum safety valve is provided in the relief line in order to prevent reverse flow of liquid after relief flow stops (due to cooling and condensation in the vent line). In addition, dependent on the specific situation it may be necessary to install some form of temperature control on the quench tank with low and high alarms and level indication also with low and high alarms.

A detailed design example has been presented recently [15].

COMPARISON OF JET CONDENSERS WITH SPARGE PIPES

A critical aspect in the design of a quench tank with a sparge pipe is the assumption that there is an even vapour distribution in a large quench tank. This is essential for the condensation efficiency and may require more than one sparge pipe.

Some uncertainties also still exist wrt. the so-called maximum allowable freeboard vapour velocity (i.e. the ratio of volumetric vapour flow rate and quench tank cross section) and the minimum required liquid level above the sparge pipe.

Research on quench tanks with sparge pipes has shown that to prevent the formation of gas/vapour channels through the quench liquid and thus incomplete vapour condensation the maximum allowable freeboard gas velocity should not exceed 0.2 to 0.3 m/s and the initial liquid level above sparge pipe should be 2 to 3 m as recommended by Schoft and Spatz [16].

These limitations often result in a quench tank size larger than the required minimum volume. Experience confirms that the difference between the two types of quench tanks may be significant in the case of very large flow rates or large quantities of non-condensables and can result in a quench tank volume with sparger pipes which is 2 to 3 times the volume of the jet condenser quench tank [16].

FUTURE TRENDS/DESIGN FOR TWO-PHASE FLOW

The extensive research carried out with jet condensers has so far been limited to single-phase flow. There would appear to be no reason why such systems should not also work for relief streams involving two-phase flow. The disposal sub-project of a major, joint industry / CEC Industrial Safety sponsored research project CHEERS (Chemical Hazard Evaluation and Emergency Relief Systems) will examine this problem. The project, which is co-ordinated by INBUREX, will develop a methodology for the design of quench tanks for two-phase flow based on a continuation of the research at the 250 l scale. In addition an industrial scale test facility is under construction involving a 10 m^3 reactor connected to a 50 m^3 quench tank fitted with jet condensers. Tests involving runaway reactions producing the three types of relief system behaviour, i.e. vapour, gassy and hybrid, will be carried out. These will be used to confirm the validity of the design methodology. If successful, it will in future be possible to design a disposal system based on a single combined knock-out and quench tank rather than the traditional two vessel systems with considerable cost savings to the process industry.

CONCLUSIONS

Extensive research has now been carried out on jet condensers for single-phase vapour flow over a wide range of pressure, temperature and quantity of non-condensables and for different vapour and quench liquid systems.

The research has enabled the development of a methodology, presented above, which allows the design of quench tanks using jet condensers to be carried out with confidence often resulting in smaller quench tank volumes than would be required when using traditional sparge pipes.

NOTATION

Symbol	Units	
A	m^2	area
c_p	kJ/kg K	specific heat capacity
C_{eff}	1	condensation efficiency
C_F	1	contraction coefficient
Δh_v	kJ/kg	latent heat of vapourization
M	kg/kmol	molecular weight
m	kg	mass
$\dot{m}$	kg/s	mass flow rate
p	Pa (or bar)	pressure (1 bar = 10^5 Pa)
R	J/kg K	gas constant
r	1	fill ratio
T	K	temperature
t	s	time
V	m^3	volume
$\dot{V}$	m^3/s	volumetric flow rate
$\dot{w}$	kg/m^2 s	mass flux
y	1	mole fraction
ρ	kg/m^3	density
ε	1	pressure ratio
κ	1	isentropic coefficient

Subscripts

crit	critical	non-cond.	non-condensed
down	downstream	up	upstream
final	final	Vap	vapour
gas	gas phase	W	quench liquid/water
init	initial		
l	liquid phase		
min	minimum		

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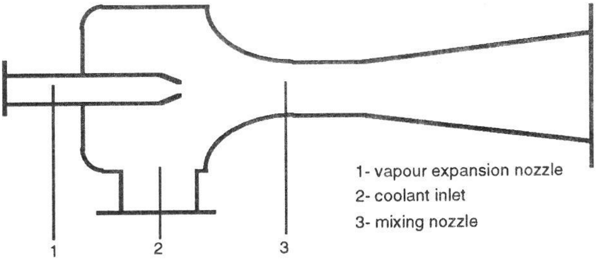

Figure 1: jet condenser operating principle

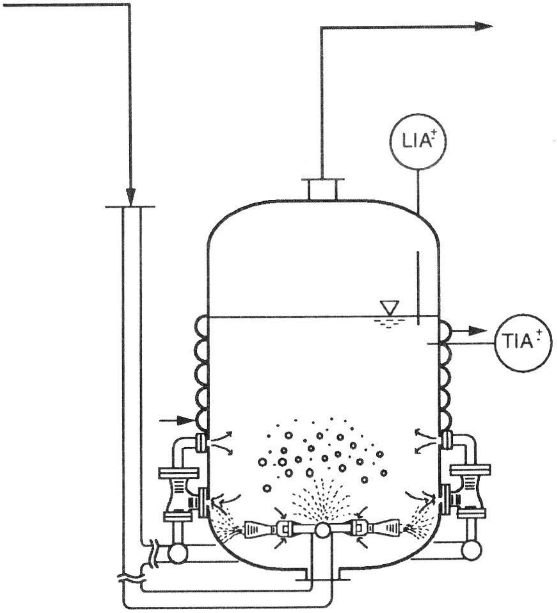

Figure 2: quench tank with jet condensers

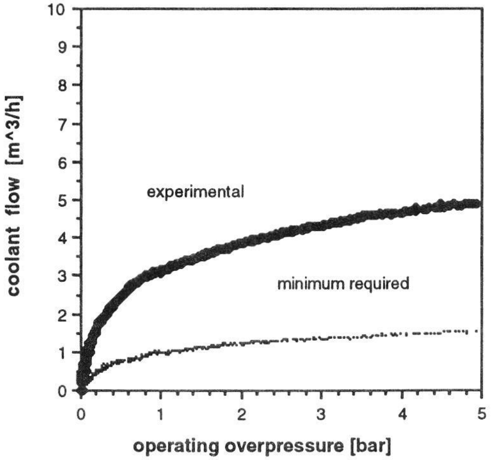

Figure 3: quenching of R113 vapour into ethylene glycol [13]

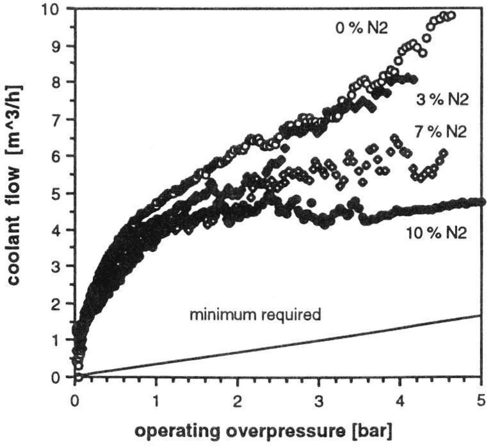

Figure 4: quenching of 2-propanol vapour into water - coolant flow rate as a function of operating overpressure given for different quantites of non-condensables (nitrogen) [14]

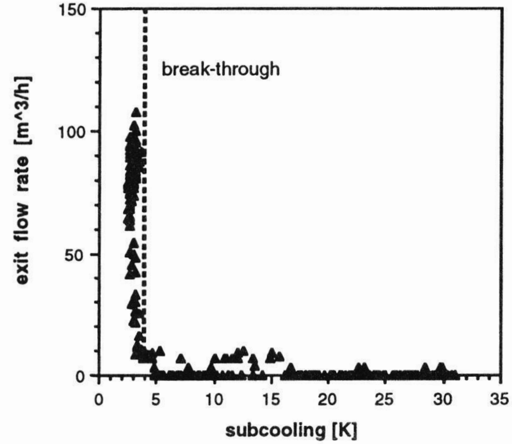

Figure 5: quenching of 2-propanol vapour into water; break-through of vapour at too low subcooling indicates incomplete condensation and thus should be avoided [12]

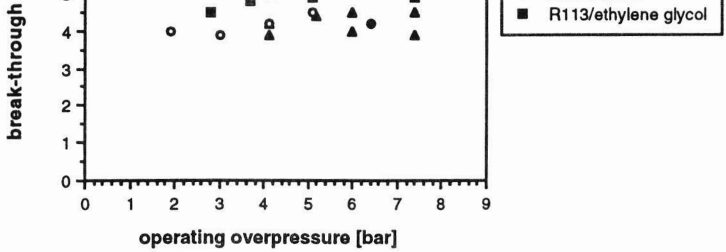

Figure 6: break-through subcooling for different systems of vapour and quench liquid [12]

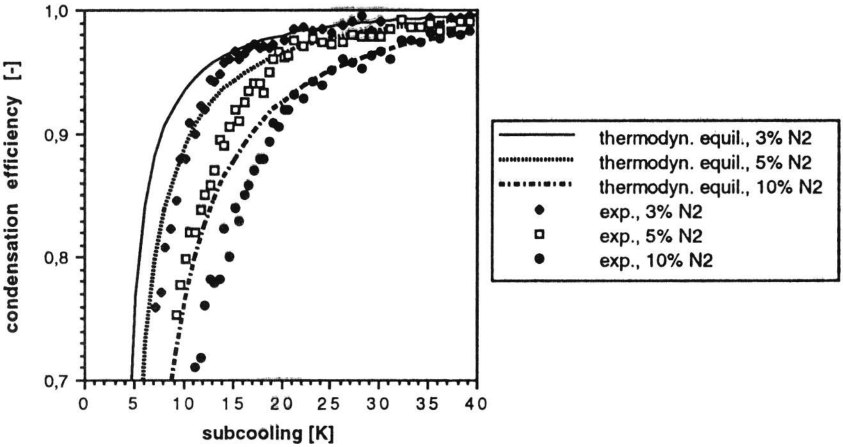

Figure 7: quenching of methanol vapour into water; condensation efficiency (experimental and predicted data) [12]

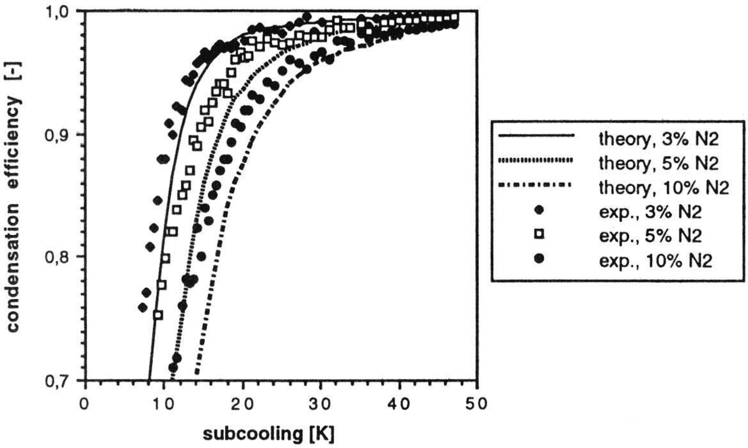

Figure 8: quenching of methanol vapour into water; condensation efficiency (experimental and theoretical data) [12]

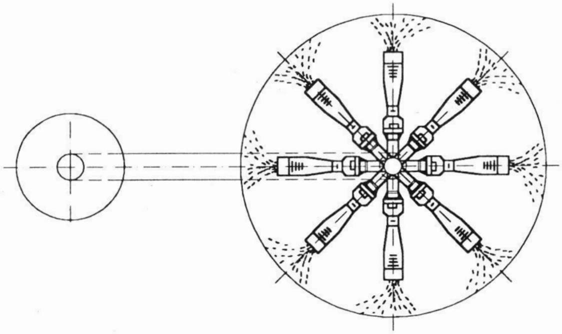

Figure 9: star arrangement of jet condensers for internal installation

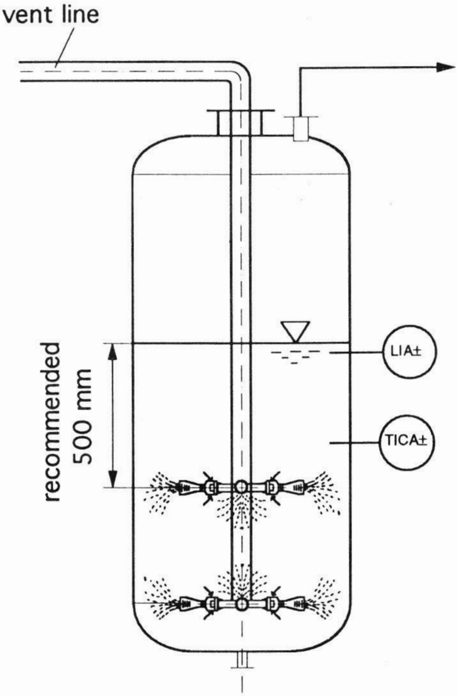

Figure 10: internal jet condenser arrangement at different levels