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Revaluating Bursting Disk Vent Sizing: The Impact of Temperature Unbalance Between Liquid and Vapor

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Bursting disk vent sizing is crucial in process industries to protect pressure vessels from overpressure. A bursting disk is a non-reclosing device that ruptures at a set pressure to safely release excess pressure. Proper sizing ensures system integrity and prevents failures, considering factors like process fluid properties, operating pressure, temperature, and relief rate. Compliance with ASME and API standards is essential, but these assume equilibrium between liquid and vapor phases, which may not hold in industrial accidents like external fires.

During a fire, liquid heats up faster than vapor due to radiation, especially without internal stirring. This temperature imbalance causes the liquid to overheat, leading to sudden vaporization when the disk opens. This effect can result in an underestimation of peak vapor flow and venting area.

This study experimentally demonstrated this temperature imbalance using a pressure-resistant calorimetric vessel equipped with a relief valve and a moving thermocouple. Findings highlight a need to reconsider vent sizing methods based on equilibrium assumptions in closed vessels for improved process safety.

* 1. Introduction

In chemical plants one of the most important concerns regards the management of potentially runaway phenomena (Pasturenzi et. al, 2014) which are capable, under certain operating conditions, of triggering strong temperature increases and, consequently, in a closed vessel, pressure increases until a possible explosion. To prevent such a hazardous consequence, it is necessary to equip the reactor with properly vent elements, as Bursting Disks (BD) or Pressure Safety Valves (PSV), having the scope to evacuate the internal overpressure thus avoiding the vessel explosion. This means that BD and PSV should be specifically designed for either the reactor in which they will be installed or the specific reaction occurring inside the vessel. In specific, to avoid that the pressure in a plant section overcomes critical values, both process control techniques and preventive analysis must be implemented. Unfortunately, in emergency situations, process control system often fails and, to avoid accidents, a detailed plant safety analysis, which has the scope to prevent these unwanted events identifying all the possible plant anomalies, is necessary (Barozzi et al., 2021). To establish which safety system must be installed on either a reactor or a vessel, it is necessary to define all the possible accidental scenarios that can determine a system overpressure, as: operative causes (rupture/failure of cooling system, human error in reactant/catalyst dosage); external fire (thermal expansion, solvent evaporation, decomposition reactions trigger); unwanted chemical reaction due to impurities (heat and gases development). Among all the most likely scenarios, the worst one must be selected to carry out the vent size design. Considering the top venting devices only, that is PSV and BD, different vent sizing methods are available in both the scientific literature and regulation standards. International vent sizing regulations for chemical reactors and vessels are primarily governed by standards such as ASME Boiler and Pressure Vessel Code (BPVC), API 520 for pressure relief devices, and NFPA 68 for explosion protection. Vent sizing methods for two-phase flow generated by runaway reactions were developed by DIERS, and ISO 4126-10 (Safety devices for protection against excessive pressure — Part10: Sizing of safety valves for gas/liquid two-phase flow) was published in 2010. After that JIS B 8227, which has the same content as ISO 4126-10, was published in 2013 in Japan (Nagasaka et al., 2019).

A common point of all these standards is that they assume equilibrium conditions in between liquid and vapors/gases inside a given vessel to properly size the venting devices. Such an assumption is not always verified at full plant scale, where temperature differences among reactor top (ref. gaseous phase) and internal liquid can be detected during whatever accidental event. In fact, it is well known that the liquid temperature is higher than that of the vapors/gases because of the bigger heat exchange efficiency of the liquid itself. This means that the liquid rises its temperature faster than the above gases, leading to delays in the pressure increase and, consequently, to the vent device opening.

In this work, it was experimentally evidenced such a temperature gradient between liquid and vapors in a closed vessel undergoing an unwanted heating process. Moreover, it was shown the impact of using either the liquid or the vapor temperature data to size a given venting device.

* 1. Sizing Method Description

In the following the main equations used by DIERS method (Fauske, 2000) will be reported and briefly commented.

The “Design Institute for Emergency Relief Systems” (DIERS) was formed in 1976 as a consortium of 29 companies to develop methods for the design of emergency relief systems to handle runaway reactions.

According to all methods proposed by DIERS, the function of whatever discharge device is to balance the production rate of fluid generated during an accidental scenario with the flowrate exiting the discharge system. The dischargeable mass flowrate depends on the flow in the blowdown line, the discharge device section, and the discharged fluid density. These parameters are lumped into the following equation:

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|  | (1) |

where: W is the mass flowrate which should be discharged (kg/s); A is the venting section (m2) and G is the discharge capacity of the blowdown line (kg/(s m2)), which takes into account all elements that can impede the flow (e.g., diameters changes and curves in the blowdown line).

Rearranging the formula, it is possible to calculate the venting section knowing the values of W and G. But, to do this, it is necessary to carefully evaluate the pressure generations modes, the vessel fluid dynamics, and the viscosity of the system.

Moreover, it is necessary to insert a suitable safety factor to take into account some uncertainties in the experimental data used to estimate the mass flowrate W. Typically, such safety factors range from 1.5 to 1.8 (referring to the estimated discharge diameter). The correct choice of the safety factor is mainly based on the type of system considered: gassy systems could use a large safety factor in comparison with vapor ones simply because the major risks associated with a reacting mixture decomposition.

Concerning the pressure generation mode, a system can be classified as: 1) vapor (where the generated pressure is due to compressible vapors production because of solvent evaporation); 2) gassy (in which generated pressure is due to incoercible gases production originated from the reacting mixture decomposition or other side reactions); 3) hybrid (in which it is possible to observe the production of both gases and vapors). Concerning the last type of system, it could be quite difficult to determine the different percentages of vapors and gases released during the accidental event therefore implying difficulties for a proper vent sizing.

For what concerns the fluid dynamics inside the vessel, it is necessary to evaluate whether the flux to be vented is either a single phase or a biphasic mixture. This can be done by evaluating the degree of swell of the reacting mixture during the accidental event. Generally, in absence of suitable information, a biphasic flow discharge is assumed for either gassy systems or vapor systems in intrinsically foamy mixtures. In this work a biphasic mixture discharge was supposed to occur in all tests where an opening of the relief valve was considered.

Finally, regarding the system viscosity, it is necessary to evaluate whether the flux in the blowdown line is laminar or turbulent. In this work, because of the viscosity of the fluid used (that is water), the flux was considered as turbulent.

According to the use of water as test fluid, a vapor system was expected and, therefore, W [kg/s] was calculated using the following equation:

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|  | (2) |

where: is the mass within the vessel [kg]; is the vessel nominal volume [m3]; is the liquid specific heat capacity [J/(kg K)]; is the self-heating rate in correspondence of either the set or the stagnation pressure [K/s]; is the latent heat of vaporization [J/mol], is the mean (between stagnation and set pressures) specific molar volume of the vapor [m3/mol] and, is the temperature at either the stagnation or the set pressure [K].

The discharge capacity of the blowdown line, G, was the same for all the experimental tests and it was calculated using the so-called ω-method (omega method). ω is a factor taking into account the non-ideal behavior of either a gas/vapor or a foam when discharged and, for vapor systems, it can be calculated using the following equation:

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|  | (3) |

where: is the reactor void fraction [-]; is the ratio between the specific heat capacity of the vapor/gas at constant pressure and volume (that is the isentropic expansion coefficient, ); is the temperature at the stagnation pressure; is the specific molar volume of the vapor at the stagnation pressure ; is the liquid vapor pressure value at the stagnation temperature

After the ω value determination, it is possible to calculate G for an ideal nozzle () and the critical pressure ratio from which the release is choked (). As this value of G does not consider the presence eventual curves or section changes in the blowdown line, it is necessary to find correction values to be applied on .

Particularly, two different types of correction factors could be implemented: 1) correction factors due to the presence of either continuous or localized pressure drops in the blowdown line, ; 2) correction factor in the case of a non-choked flow, , that is taking into consideration a stagnation pressure lower with respect to the critical pressure value (previously determined knowing the ω value, that is ). The final expression of G can be calculated using the following equation:

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|  | (4) |

where: is the stagnation pressure (Pa) and is the specific volume of the flux at the stagnation conditions (m3/mol).

* 1. Materials and methods
     1. Reaction Calorimeter

The reaction calorimeter used for this study was an EasyMax 102 workstation (Mettler Toledo), which allows to carry out experiments in a temperature range between -40 °C to 180 °C, using a cooling-heating system based on Peltier cells.

In the case of the experimental tests carried out in this work, the selected calorimeter was operated under a Tj-mode able to maintain the external reactor walls at a given constant temperature (both 172°C and 140°C).

Since a fundamental part of this work was to measure the pressure in correspondence of the various temperatures over time, it was necessary to use a pressure resistant calorimeter, EM20-100-HC (Mettler Toledo), compatible with the EasyMax 102 workstation. This vessel is constructed in a Ni-Cr-Mo alloy called C-22 which allows the vessel to tolerate high temperatures, aggressive environments, and pressure until 65 bar. The instrument is equipped with a thermocouple capable of measuring internal temperature at different heights (both in the liquid and vapor phases), an hermetically sealed stirrer having a magnetic coupling between engine and anchor/propeller, a BD to avoid overpressures over 65 bar and a relief valve. The system to be studied was considered as non-reactive (water) and temperatures, in both liquid and gas phase, were measured varying the position of the thermocouple inside the reactor.

* + 1. Experimental Protocol

Each experimental test was designed adhering to the following protocol (with minor variations from one test to another one):

1. Loading of a given mass of distilled water (50 or 60 g) into the calorimeter;
2. Reactor hermetic sealing and thermosetting at 20°C, with a stirrer speed set to 50 rpm;
3. Start of jacket warm-up, set at different temperatures (172 °C or 140 °C), to simulate the presence of an external fire. In the meantime, pressure values at different times were collected in an Excel file;
4. Alternatively, both liquid and gas phase temperatures were collected;
5. When a maximum temperature value was reached for both liquid and gas phases, two different types of experiments were carried out: 1) the system was kept sealed for a given period of time (just to ensure the reaching of a thermal equilibrium); 2) the relief valve was opened (the pressure values during the vent were recorded in a video and collected in a second time);
6. The calorimeter was then set at the final temperature of 25 °C.

With this experimental protocol, it was possible to demonstrate the presence of a thermal gradient between liquid and gas responsible for a slower increase of the gas temperature with respect to the liquid one; this is mainly due to the fact that gas temperature is affected by heat losses from the reactor top and it is heated in a less efficient way by the reactor walls (heated by the workstation set at a given Tj temperature). A major part of heat responsible for the gas temperature increase comes from the rising vapors from the liquid surface; this leads to have a liquid at a higher boiling temperature with respect to that one corresponding to the actual pressure registered in the gaseous phase (roughly evaluable by using an ideal gas law). Within this work, 5 calorimetric tests on distilled water were carried out using: 1) different jacket temperature settings, 2) closed or open systems, 3) alternate temperature measures in between liquid and vapor, and 4) different vessel filling levels.

* 1. Results
     1. Closed cell tests

In the first set of experiments, a filling level equal to 50 mL of distilled water and a jacket set-point temperature of 172 °C were selected. Particularly, the first test was carried out inserting the thermocouple “into the liquid” while the second one was done fixing the position of the thermocouple at about 10 mm higher than the liquid surface, that is “into the bulk of the gas phase”. No venting was done at the end of each test: that is, the tests were referred to as “closed cell tests”. The experimental protocol was in accordance with that one reported in paragraph 3.2. These tests were then used for vent sizing purposes.

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*Figure 1:* a) Temperature vs. time and, b) Pressure vs. time profiles for two simulations of external fire. Thermocouple in either the gas (continuous line) or the liquid (dotted line) phase.

Figure 1 reports both temperature (a) and pressure (b) profiles over time for the two different tests. As it can be observed, under the same heat flux from the “simulated external fire”, there is clear difference between the temperatures registered in either the gas or the liquid phase: particularly, the temperature measured by the “liquid thermocouple” was always higher than the temperature measured by the “gas thermocouple”, with difference values ranging from 10 to 20 °C. On the contrary, pressure registered are practically uninfluenced by the position of the thermocouple: this is because the pressure was measured by a manometer located at the top of the reactor (that is, into the gas phase). Moreover, the gas phase needed more time to reach equilibrium conditions with respect to the liquid phase.

* + 1. Open cell tests: “Bursting Disk” Opening Simulation

In the second set of experiments, a filling level equal to 60 mL of distilled water and a jacket set-point temperature of 140 °C were selected. Particularly, the first test was carried out inserting the thermocouple “into the liquid” and, then, at different pre-determined instants, shifting it into the gas phase for a given period of time and, successively, re-shifting it into the liquid (this operation was done many times); while the second one was done starting the position of the thermocouple into the gas phase and, at the roughly same instances of the previous test, moving the thermocouple into and out to the liquid phase. A rapid venting (the relief valve was opened at the set pressure and maintained open) was done at the end of each test: that is, the tests were referred to as “open cell tests”. The experimental protocol was in accordance with that one reported in paragraph 3.2. It is important to note that this rapid venting corresponds to the simulation of a real bursting disk installed onto a reactor.

Observing Figure 2, it is possible to note that: 1) the differences between the temperatures of either the gas or the liquid phase ranged from 10 to 30 °C, also confirming the slower thermal dynamics of the gas with respect to that of the liquid; 2) when the “bursting disk” was opened, the liquid temperature decreased rapidly till the value of 100 °C, which is the boiling temperature of water at ambient pressure (in fact, due to the reduced size of the reactor, there was a “quasi-instantaneous” depressurization of the vessel); 3) when the “bursting disk” was opened, the gas temperature first slightly increased, then rapidly decreased till a value of 98 °C (a little bit lower than the liquid temperature because of the heat dispersions).

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Figure 2: a) Temperature vs. time profiles for tests with the thermocouple starting in either the liquid (red continuous line) or the gas (black circles) phase; b) zoom in of the two relief periods.

* + 1. Open cell test: Relief Valve and Bursting Disk Opening Simulation

In the last experiment, a filling level equal to 50 mL of distilled water and a jacket set-point temperature of 172 °C were selected. Particularly, the test was carried out starting the thermocouple “into the liquid” and then, at different instants, shifting it into the gas phase for a given period and, successively, re-shifting it into the liquid (many times). Finally, maintaining the thermocouple into the gas phase, a first venting was activated in correspondence of 1379 s and, a second one was activated 138 s later. The first venting wished to simulate the intervention of a relief valve (slow dynamics of opening and maintenance of the system in a tempered state), while the second one wished to simulate the intervention of a bursting disk.

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Figure 3: a) Temperature vs. time profiles for the test with the thermocouple starting in the liquid and, then, alternatively switched between liquid and vapor; b) zoom in of the two relief periods.

As it can be noted observing Figure 3, the temperature unbalance between gas and liquid was always maintained. When there was the activation of the first relief (that one simulating the opening of a relief valve), an increase in the gas temperature was observed over a period of around 20 seconds. Then, a decrease in the gas temperature occurred till the reaching of the “tempered point”, which was in correspondence of 120 °C. In fact, without any further increase in the degree of opening of the relief valve, the system remained partially pressurized. Finally, when the relief valve was totally opened (maximum possible degree of opening), a “quasi-imperceptible” gas temperature increase was observed, immediately followed by a rapid decrease. This phenomenon can be easily explained considering that, during the first slow opening of the “safety device” the hot vapors coming from the superheated liquid had enough time to warm up the gas phase; moreover, as the degree of opening of the relief valve is not capable of providing a total depressurization of the vessel till the atmospheric pressure, a new equilibrium point is reached (tempering). On the contrary, during the second relief when the valve was immediately and totally opened, the rapid depressurization of the vessel did not permit to observe any temperature increase and the gas temperature quickly approached the liquid one (which was the boiling temperature at ambient pressure, because a complete vessel depressurization occurred).

* + 1. Vent sizing evaluations

As resumed in paragraph 2.1, DIERS method for vent sizing of vapor systems makes use of Eq. (2), where the self-heating rate in correspondence of both the set and the stagnation pressure appear. According to the results presented in paragraph 4.1, the use of either the gas or the liquid temperature and its derivatives can lead to different results. Referring to Table 1, it is possible to calculate a ratio between the venting area determined using either the gas temperature data or the liquid temperature data equal to 0.57. This means that using the gas temperature data can lead to a strong reduction in the vent sizing area. Particularly, also considering the blowdown line installed for the experimental system, it was possible to calculate a venting diameter equal to 1.46e-02 cm considering the temperature data in the gas phase and 2.56e-02 cm considering the temperature data in the liquid phase. Such diameters are smaller than the venting area available (which was 3.99e-01 cm) because they were calculated using equivalent supplied powers for water evaporation ranging from 50 to 150 W. To discharge a flux corresponding to the installed venting area, a supplied power over 100 kW should be provided; this was not the case, but it could happen when a strong reacting mixture decomposition occurs.

Table 1: Parameters for calculation of W (DIERS method)

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| --- | --- | --- | --- | --- | --- | --- |
| Parameter | Value | Unit |  | Gas Phase  Value | Liquid Phase  Value | Unit |
|  | 50 | *g* |  | 9.05e-4 | 2.15e-3 | K/s |
|  | 4.184 | J/(g K) |  | 1.92e-3 | 1.86e-3 | K/s |
|  | 100 | mL |  | 104.7 | 131.05 | °C |
|  | 40800 | J/mol |  | 107.8 | 132.48 | °C |

* 1. Conclusions

In this work, it was demonstrated that, during an accidental event (e.g., an external fire), a temperature unbalance between liquid and vapors in a closed vessel can occur.

This means that using temperature data coming from either the liquid or the vapors give rise to different mass flux to be discharged by the blowdown line.

In particular, the ratio among the calculated venting areas (gas on liquid) was 0.57. Such a value obviously depends on either the thermal inertia factor or the isolation efficiency of the system, but it should be considered for a more precise vent sizing, especially for vapor systems at industrial scale.

Moreover, the most notable effect of the temperature unbalance was the rapid increase in the gas temperature observed when simulating a safety valve opening. This phenomenon could imply some safety concerns in an industrial equipment therefore it should be deeply investigated in the near future.

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