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Influence of a Wall Close to a Vent Outlet

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Abstract

It is well known that the US NFPA 68 (2013) and the EU standard (EN14994:2007), based on the work of Bartknecht (1993), for gas venting do not agree and the EU standard will require a much larger vent area for the same P_{red}. The present work offers a possible explanation of the difference in these guidelines: the experimental results of. Bartknecht (1993) were carried out with the bottom of the vented vessel on the ground, so that the vent exit was relatively close to the ground and the interaction increased P_{red}. In the present work a 0.2 m^3 cylinder of 0.5m diameter with end wall ignition was free vented into a large dump vessel with a 0.5m diameter connecting pipe. The wall of the 0.5m connecting pipe was close to the vent and the results showed that there was a wall interaction that gave P_{red} close to those of Bartknecht (1993) at low K_v. In the vented explosion work of Fakandu (2016b) using a 10L vessel, the discharge area was connected to a dump vessel with a 0.5m diameter pipe, which was much bigger than the 162mm diameter of the vented vessel and this gave overpressures close to those predicted in NFPA 68 (2013) with the turbulence parameter λ set to unity. The critical ratio of the centerline distance of the vented vessel to the external surface (ground in most cases) as a ratio of the distance from the edge of the vent to the external surface (DR) was shown to be 1.8 in this work, with lower values indicating no interaction. The present results show that Bartknecht's experimental results had high P_{red} probably due to the presence of the ground as a nearby surface.

Introduction

The peak overpressure, P_{red}, in vented explosions has several causes (Fakandu et al., 2016b), but for low (<10) values of the vent coefficient, K_v ($V^{2/3}/A_v$), the backpressure caused by the external explosion has been found to be the source of the peak over pressure (Fakandu et al., 2016b). The vent coefficient, K_v, includes the effect of vessel volume so that experiments on a small scale, such as the 10L cylindrical vented explosion vessel used by Fakandu et al. (2016b), should have the same P_{red} as for a 100 m^3 vessel for the same K_v, vessel geometry and ignition position. However, the literature on this is not clear as shown by the comparison of vented explosion results for 4-4.5% propane-air in Fig. 1 (Fakandu et al., 2016b).

The USA (NFPA68, 2013) and European (EN14994:2007) gas explosion vent design equations are also shown in Fig. 1 for comparison. The USA guidance, for a turbulence factor of 1, agrees with laminar flame venting theory (Fakandu et al, 2016b; Andrews and Phylaktou, 2010), for vent discharge coefficients of 0.61 and 0.7, as shown in Fig. 1. The laminar flame theory should overpredict P_{red} as it assumes that the flame area is the same as

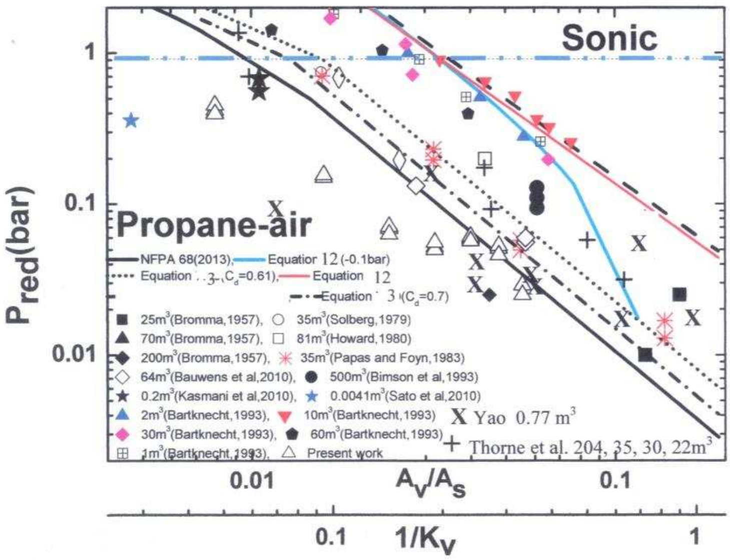

Figure 1: Propane-air free venting explosion data for different vessel volumes compared with EU and NFPA68 guidance.

the surface area of the vessel at the time P_{red} occurs, when it is known that this is not the case (Cates and Samuels, 1991). Fig. 1 shows that the results of Fakandu et al. (2016b) fall below the NFPA 68 (2013) guidance and most results for larger volumes scatter around the design line. Fig. 1 also shows that the USA guidance, with the turbulence factor λ set at 1, is also a good predictor of most of the experimental results for free venting, apart from the results of Bartknecht (1993). In contrast the European vent design predictions (EN14994:2007) only agree with the results of Bartknecht (1993), on which they are based. It is clear that the two vent design standards do not agree and the European design standards are in disagreement with all experiments in the public domain, apart from Bartknecht's work (1993).

The present work offers a possible explanation of the difference in these predictions and experimental results. Bartknecht carried out all his experiments with the bottom of the vented vessel on the ground, so that the vent exit was relatively close to the ground. In addition he changed the vent area by opening panels in the vent wall, so that the vent was not central and was closer to the ground as the vent area was increased. In contrast many other experimental investigators had the vented vessel on legs so that the vent external jet flame was a greater distance from the ground than in the case of Bartknecht (1993). It is possible that one of the differences between the experimental results in Fig. 1 was that each investigator had a different distance from the vent to the ground and that this influenced P_{red}.

In the present work a cylindrical tube was placed around the vent exit that was the same diameter as the vented cylindrical vessel, the results show that there was a wall interaction with P_{red} values close to those of Bartknecht at low K_v. In the vented explosion work of

Fakandu et al. (2016b) using a 10L cylindrical vessel, the discharge area was connected to a dump vessel with a 0.5m diameter pipe which was much bigger than the 162mm diameter of the vented vessel.

2. Experimental Methods

The small 10L vented explosion vessel with a diameter of 162mm and an L/D of 2.8 is shown in Figure 2 and Figure 1 shows the P_{red} results for this vessel with end wall ignition, where they are compared with other vented vessel P_{red} from the literature. Figure 1 is for free venting

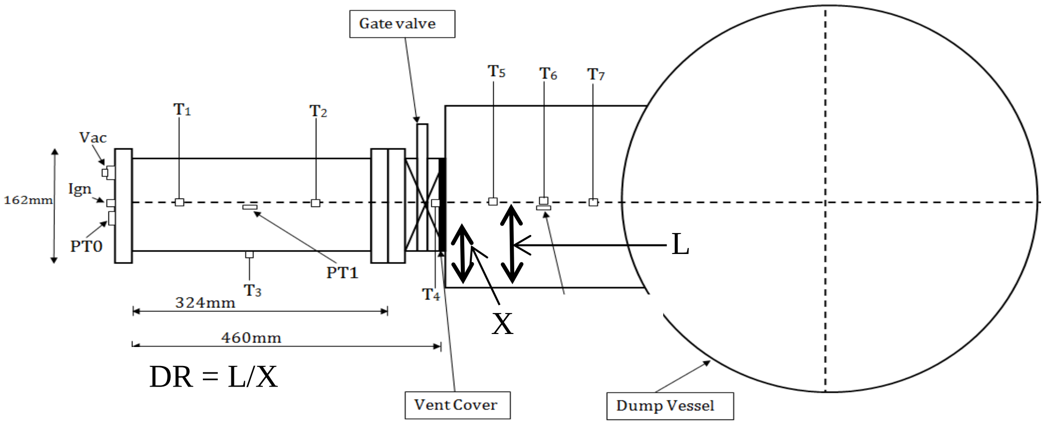

Figure 2: 10L small vented vessel with a large vessel surrounding the vent outlet

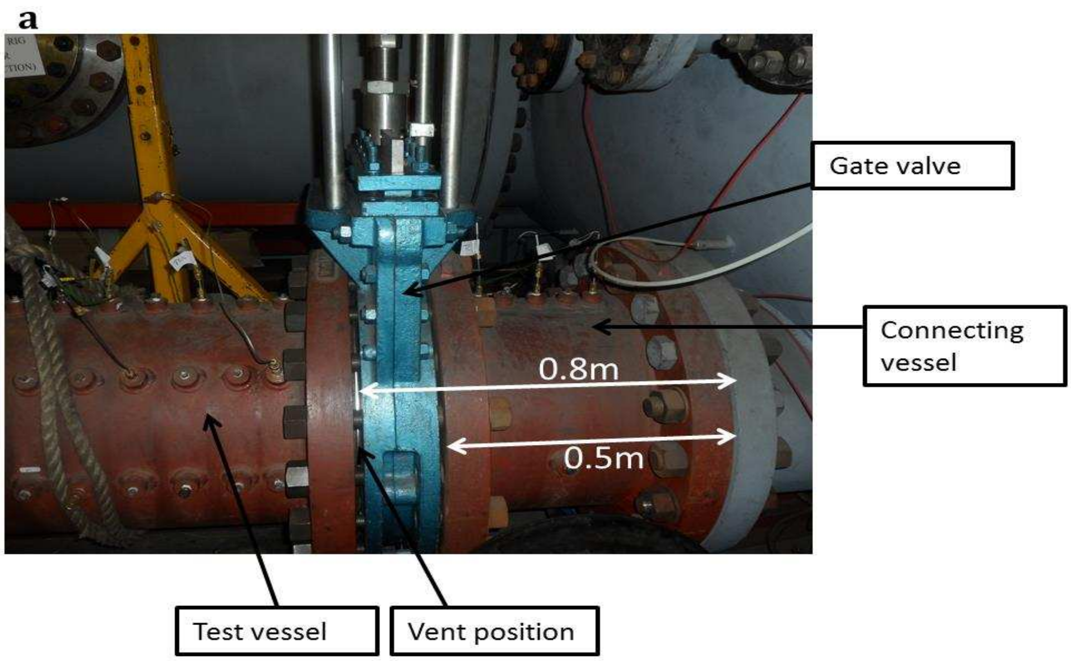

Figure 3 Experimental test rig

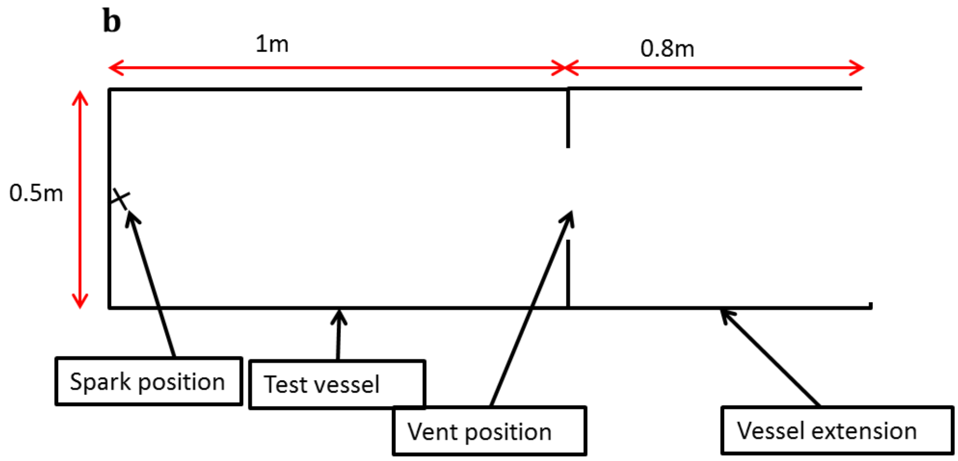

Figure 4: Geometry of the test facility.

or very low P_{stat} venting. It shows that the 10L vented vessel has P_{red} values close to the laminar flame venting predictions. The vent outlet was connected to the dump vessel using a 0.5m diameter pipe connection. The distance from the centreline of the vented vessel to the discharge vessel wall (L = 0.25m) as a ratio to the distance from the bottom of the vent to the vented vessel inner wall for the largest vent tested (20% blockage) the DR, was 1.41 and for the smallest vent tested (90% blockage) the DR was 1.11. Thus it can be concluded that if the DR is about 1.4 or less then there is no interaction with the wall surrounding the vented jet. The present work will show that there is a critical value, DR_{crit}, of about 1.8, above which P_{red} increases due to interaction with the external wall and all the geometries tests in the configuration of Figure 1 lie below this value.

In the present work a 200L vented vessel was used, as shown in Figure 3. This vessel was also used by Kasmani et al. (2007). This vented vessel was 20 times the volume of the smaller 10L vessel used in previous work by the authors (Fakandu et al., 2015, 2016a,b). The intention was to study the scale up of the volume of the vented vessel for the same K_v. The 0.2m^3 vessel was 0.5m diameter and 1m long and had an L/D of 2. The discharge wall of the vessel housed the central circular vent and there was a downstream 0.5m diameter vacuum gate valve that was opened just prior to the test. The vacuum gate valve enabled gas mixtures to be made up using partial pressures with the flammable gas added under vacuum conditions and then air added to make the pressure up to a standard atmosphere.

The vented vessel was connected to a 50m^3 dump vessel with a 0.5m diameter pipe 0.8m long connecting duct. The test geometry is shown schematically in Fig. 4. For this vessel the distance from the centerline of the vented vessel to the outer wall surface as a ratio of distance from the bottom of the vent to the vessel wall (DR = L/X in Fig. 2) varied with K_v from 3.2 to 9.5. The size of the vent was varied to cover a range of K_v and the vented tests were carried out at 10% methane-air and 4.5% propane-air, which are the most reactive mixtures. The vented vessel had a linear array of open bead thermocouples on the centerline of the vessel and down the discharge pipe. These were used to determine the flame speed. A piezo resistive pressure transducer was fitted flush with the wall to determine the pressure time record. There was a thermocouple located in the vent plane to determine the time the flame left the vent.

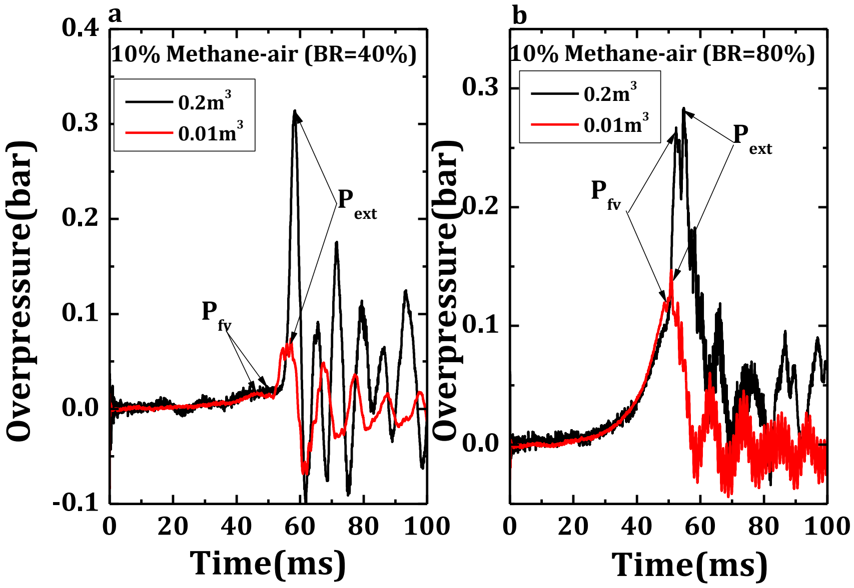

Figure 5: Pressure-Time for 10 and 200L cylindrical vessel volumes for 10% methane-air

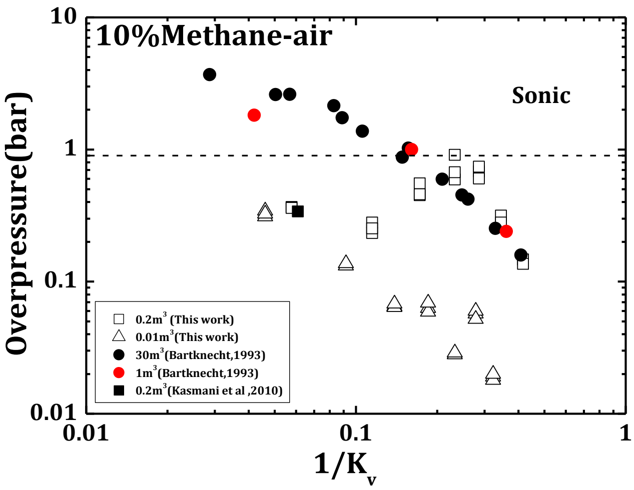

Figure 6 Comparison of 10L and 200L result with Bartknecht (1993) for 10% methane-air

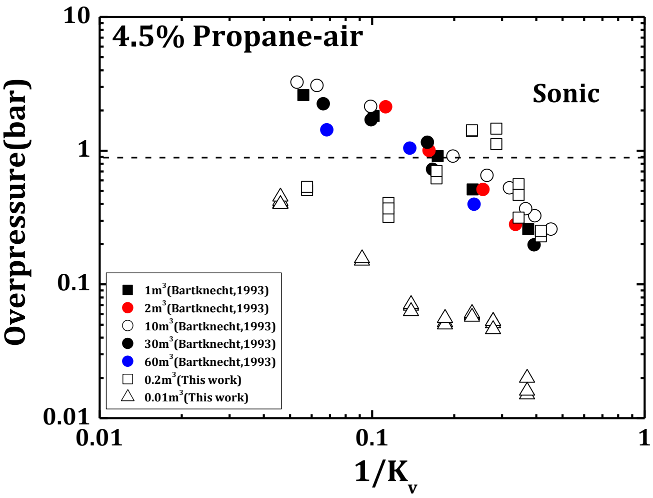

Figure 7 Comparison of 10L and 200L results with Bartknecht (1993) for 4.5% propane=air

3. Results

Typical pressure time records of the vented explosions for 10% methane-air are shown in Figure 5 for a vent blockage ratio of 40 and 80% which for the 10L vessel volume are a K_v of 3.78 and 11.26 respectively and for the 200L vessel are a K_v of 2.91 and 8.76. The small difference in K_v for the two vessel was due to differences in the vessel L/D, 2.8 for the smaller vessel and 2.0 for the larger vessel. The time scales in Fig.5 have been adjusted for the 200L vessel using the cube root of volume time ratios for the same overpressure. This time correction places the venting events on a similar relative time scale, but the small differences in time that events occur should not be taken as significant due to the differences in L/D.

Figure 5a, for the larger vent size or lower K_v, shows that the pressure rise up to the point of the flame leaving the vent were the same for the two volumes. Thus, the flow through the vent pressure rise, P_{fv}, was not influenced by the difference in the vessel volume for low K_v. However, at low K_v or low vent blockage, the external explosion dominated the peak overpressure, P_{red}, and was much higher in the larger vessel. It has been shown in previous work by the authors (Fakandu, et al., 2016b) that the external explosion controls P_{red} for low K_v (<~10) and P_{fv} controls P_{red} for higher K_v, but the difference in the two overpressure were small at all K_v. Where the external explosion is the largest of the pressure peaks, it appears that the presence of a wall close to the vent outlet increases P_{red} through an increase in P_{ext}. This is due to the creation of a vortex ring at the vent outlet in vented explosions that is constrained by the presence of the wall, which increases the back pressure.

Figure 5b shows that for the smaller vent and higher K_v both vessel volumes had similar P_{fv} and P_{ext}, but both were much higher in the larger 200L vessel. The P_{ext} due to the presence of walls close to the vent in the larger volume was smaller for the smaller vent than for the larger vent in Fig. 4a. This could be due to the shorter distance from the edge of the vent to the outer wall at low K_v, so that DR was higher and the effect of the external wall greater. The differences in K_v for the same vent flow blockage are not large enough to account for the large difference in the peak external pressure, as can be seen in Figure 1. These higher P_{red} in the larger vessel volume clearly have a cause that is greater than laminar flame venting theory would predict.

Figure 6 shows the P_{red} result of vented explosions as a function of $1/K_v$ for the 200L vessel with the vessel extension for 10% methane-air. Figure 6 also shows the P_{red} results for the 10L vessel (Fakandu, et al., 2016b) and the experimental data of Bartknecht (1993) for different vessel volumes from 1 – 60 m^3. Figure 7 shows the equivalent data for 4.5% propane-air vented explosions and the trends were similar for both fuels. The P_{red} for the 200L vessel were much higher than for the 10L vessel for K_v greater than 8.3 for methane and propane and were similar to or higher than Bartknecht's results for volumes 1-60 m^3. Figure 1 shows that the 10L vented vessel results of the authors are in reasonable agreement with a wide range of other vented vessel data over a range of volumes. The agreement with Bartknecht's (1993) data of the present 200L vented vessel results with a downstream surface external to the vent in Figures 6 and 7 show that it is probably not an effect of the larger vessel volumes used by Bartknecht (1993) that gave the higher P_{red}, but the effect of the ground being close to the vented jet in Bartknecht's (1993) experiments.

For a K_v of 17.5 (90% blockage) the 200L vessel results were similar to those for the 10L vessel for both propane and methane vented explosions. This was the smallest vent and had the greatest distance from the external wall and a DR ratio of 2.72, which must be close to the critical DR for wall interaction effects to increase P_{red}. A DR above 2.7 will be required for external wall interaction to be significant. Figures 5 and 6 show that for a K_v of 8.3 (80% blockage) or lower the wall interaction caused the P_{red} to increase for the 200L vessel compared with the 10L vessel. This is a DR of 1.81 and so it may be concluded that the critical DR for external wall interaction effects to increase P_{red} is between 1.8 and 2.7 and the critical DR is probably 1.8, with higher values resulting in significant external wall interaction effects. This is in agreement with the test geometry in Figure 2, where the DR varied from 1.11 – 1.43 for the range of K_v investigated with no wall interaction effects. Kasmani (2007) found a strong external wall interaction effect for the present 200L vessel with a K_v of 17.5 if the external connecting pipe was reduced to 324mm where the DR was 2.0, this confirms that a DR of 1.8 is the most likely critical value of DR above which strong external wall interaction effects will occur. Kasmani (2007) also showed that this elevated P_{red} with a DR of

1.8 did not occur for lean mixtures where P_{red} was much lower, close to that of laminar flame venting theory. It was only the maximum reactivity mixture that give the higher overpressure.

Figures 5 and 6 show that the results with the 0.5m diameter vessel and 0.5m diameter outlet extension are similar to the geometry of Bartknecht (1993) with the ground close to the vessel vent, which could give a wall interaction effect that is probably related to the coanda effect of jets close to walls. The agreement with Bartknecht's data was for K_v< 7.2 in which the P_{ext} was the controlling peak pressure. In this case, the jet of flame exiting the vent ignited the external cloud close to the vent, within the vessel extension, thereby making contact with the lower and upper walls of the vessel extension. The vortex of the external jets was not allowed to be fully established as for the case of venting directly into the atmosphere. Bartknecht's (1993) vented vessel had the bottom of the vessel on the ground so that the bottom of the vent was close to the ground and DR was likely to be <1.8 in most cases, although exact geometries of the vessels are not known. The present work with an external surface surrounding the vented jet may not give the same external wall interaction as a flat surface on one side of the jet. Many vented vessel in the literature mount the vessel close to the ground and very few used vertical venting, where this problem would not occur. Much of the data scatter at constant K_v in Figure 1 could be due to differences in DR between the various vented explosion experiments.

Fig.8a compares the 10L and 200L vessels vent overpressures for the peak pressure just before the flame left the vent, P_{fv}. This pressure was caused by the explosion induced flow of

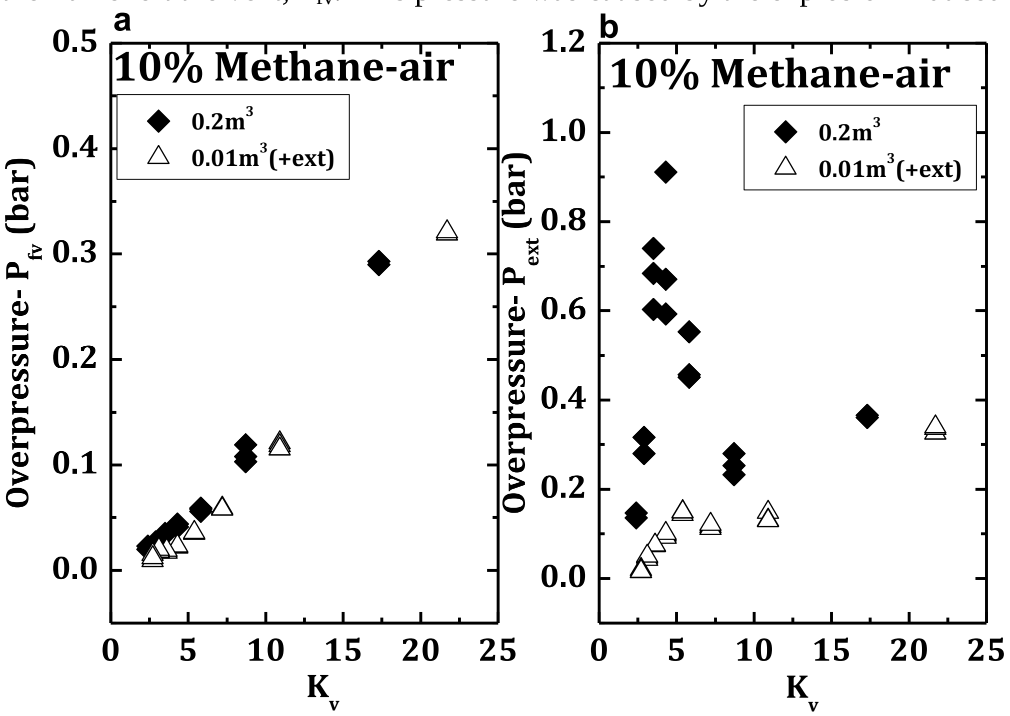

Figure 8: Comparison of P_{red} as a function of K_v for the 10 and 200L vessels for 10% methane-air: (a) P_{red} flow through vent (b) P_{red} external explosion.

unburnt gas through the vent. This shows very good agreement between the two vessels with the 200L vessel P_{fv} slightly higher than that for the 10L vessel. This is the overpressure that laminar flame venting theory predicts.

Figure 8b shows the external peak overpressure, P_{ext}, as a function of K_v. This is determined as the peak pressure after the flame has exited the vent. This clearly shows a higher P_{ext} for the larger vessel for K_v from 2 to 8. This high P_{ext} overpressure relative to the 10L vessel was not found for a K_v of 17.5. This indicates that at high K_v and low DR there was no surface interaction on the discharge side of the vent in the 200L vented vessel. It is clear that it is the external explosion that is enhanced when external wall interaction effects are significant in vented explosions.

As a further check on the importance of wall interaction effects downstream of the vent, the small vented vessel was set up in the same configuration of Figure 3 with a downstream pipe of the same diameter as the vented vessel. The test rig is shown in Fig.9 and the discharge from the 0.26m long 0.162m diameter downstream pipe was into a 0.162m diameter pipe which connected to the dump vessel. In this configuration the range of DR for the range of K_v investigated (blockage ratio from 20 to 90%) was 1.46 to 9.5, the same as for the 200L vessel with 0.5m downstream discharge pipe.

The results for the P_{fv} and P_{ext} are shown in Fig. 10 as a function of K_v for free venting. The effect of the 0.162m diameter pipe discharge on the 0.162 diameter 10L vented vessel was to increase the P_{ext} with no influence on $P_{fv.}$ This is identical to the results for the 0.5m vented vessel. However, the magnitude of the influence of the downstream pipe was different with the increase in P_{ext} lower than in Figure 8b for the 0.5m diameter vented vessel. This may indicate that the external surface interaction effect is greater for large sized vessels, but more work is required to verify this. For K_v of 11 (DR 2.24) there was only a small increase in P_{ext} and for a K_v of 22 (DR 1.46) there was no increase in P_{ext} with the addition of the downstream pipe. This again supports the above conclusion that the critical DR for no effect of a downstream wall close to the vent outlet is 1.8, with lower values having no wall interaction.

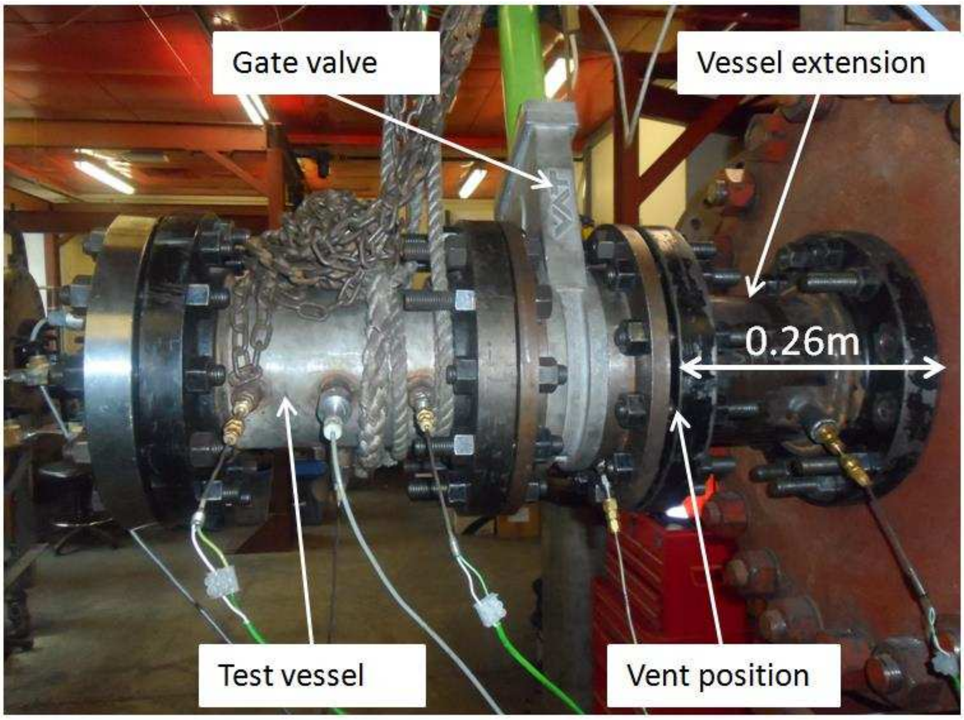

Figure 9: The 10L vented vessel with an extension pipe the same diameter as the explosion vessel.

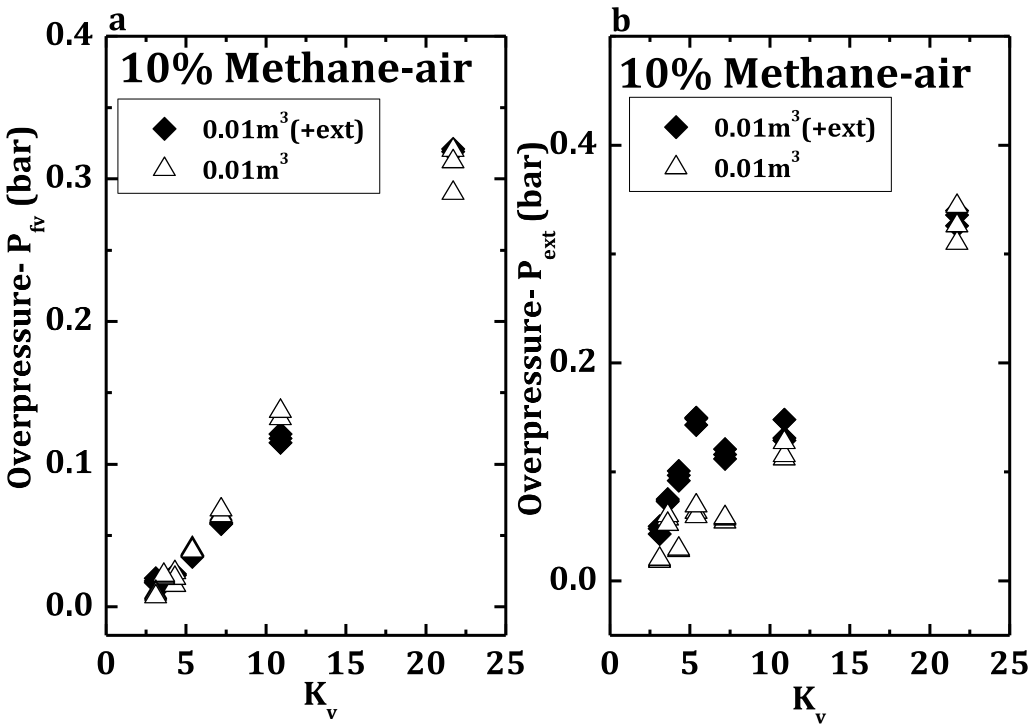

Figure 10: Comparison of $0.01m^3$ with $0.01m^3$(+ext) (a) P_{fv} (b) P_{ext}

4. Conclusions

The scale up of a 10L cylindrical vented vessel to 200L resulted in a large increase in P_{red} for the same K_v, apart from for the highest K_v of 17.5, where the two volumes were in agreement. The higher P_{red} for the 200L vessel was a similar P_{red} to that measured by Bartknecht (1993) and which the EU venting standards are based. The increase in P_{red} was much larger than any known volume effect would give and it was considered that there was another factor that increased P_{red}. The 200L vessel was 0.5m diameter and was connected to a large dump vessel with a 0.5m cylindrical outlet pipe connecting the two vessels. The proximity of a wall close to the vent outlet was a possible explanation of the increased P_{red} in the 200L 0.5m diameter vessel. The distance of the centreline of the vented vessel to the external surface (L) divided by the distance of the edge of the vent to the external wall (X) was termed a distance ratio (DR). The action of K_v was to decrease DR as K_v was increased (smaller A_v and larger X) for a fixed L. In the 200L vented vessel it was shown that the critical DR was 1.8 and above this value there was no increase in P_{red} relative to results with a wall a long distance away from the vent. In the smaller 10L vessel the connection to the large dump vessel was via a 0.5m pipe and DR was 1.1 – 1.4 and there was no interaction with the external wall. For vented vessels mounted on the ground, as in the work of Bartknecht (1993) and others, the distance of the vent to the ground may give a similar surface interaction effect and may be the reason that Bartknecht's P_{red} are much higher than for other data for the same K_v. The present results show that a wall in close proximity to the vent outlet should be avoided in vent installations, as the increase in P_{red} with this interaction is very large. This should be mentioned in vent design standards as an installation geometry that should be avoided.

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