Conference or Workshop Item:

Fakandu, B, Tomlin, G, Phylaktou, HN et al. (1 more author) The Influence of Vessel Volume at Constant Kv for Vented Gas Explosions. In: 12th International Symposium on Hazards, Prevention and Mitigation of Industrial Explosions (12th ISHPMIE 2018), 12-17 Aug 2018, Kansas City, MO, USA.

The Influence of Vessel Volume at Constant K_v for Vented Gas Explosions

Fakandu, B.[a], Tomlin, G.[b], Phylaktou, H.N. [c], Andrews, G.E.[c]

[a] Nigerian Military Academy, Nigeria

[b] DNVGL Spadeadam Explosion Test Site

[c]School of Chemical and Process Engineering
University of Leeds, LS2 9JT, UK

profgeandrews@hotmail.com

Presented at the
12th International Symposium on Hazards, Prevention and Mitigation of Industrial Explosions (12th ISHPMIE 2018)
August 12-17, 2018, KANSAS CITY, USA

CONTENTS

1. Vent Area for Different Volumes: Dimensionless Terms
2. The use of the vessel surface area, A_s, in NFPA68.
3. The vessel volume effect indirectly included in the turbulence factor in NFPA68.
4. Vessel volume effect in dust explosion venting
5. The vessel volume effect in the self acceleration term in NFPA 69, critical volume for onset of self acceleration.
6. Review of Experimental Data as P_{red} v. $1/K_v$ or A_v/A_s for vessel of different volume
7. Review of Experimental Data on the Volume Effect for Gas Explosion Venting at low P_{stat} and constant K_v
8. Conclusions

Vent Area for Different Volumes – Dimensional terms - 1.

Vent design standards use different ways to express the vent area as a function of the volume, V.

In the EU design procedures the vent coefficient, $K_v = V^{2/3}/A_v$, is used (but not stated as such as A_v = const $V^{2/3}$

so $1/K_v$ = const. which depends on the mixture reactivity).

For a cubic vessel $V^{2/3}$ is the cross-sectional area A and British Gas and their successor DNVGL still use the area ratio A/A_v for venting correlations. However, most workers now use K_v as this is independent of the shape of the vented vessel

In the USA NFPA68 2013 A_v/A_s is used where A_s is the surface area of the vented vessel.

However, as A_s = const. $V^{2/3}$ these methods are related. In this work the constant is referred to as C_2

An overall prediction equation for vented explosions for gases was generated by Bartknecht. (Bartknecht, Explosions, 1993, p.480, Springer Verlag)

$$A_v=[(0.1265\log K_G-0.0567)P_{red}^{-0.5817}+0.1754P_{red}^{-0.5722}(P_{stat}-0.1)]\ V^{2/3}$$

This may be also expressed in terms of $K_v = V^{2/3}/A_v$

$$1/K_v=(0.1265\log K_G-0.0567)P_{red}^{-0.5817}+0.1754P_{red}^{-0.5722}(P_{stat}-0.1)$$

The first term of this correlation is the vent flow pressure loss term for 100mb P_{stat} and the second terms is the additional influence of P_{stat}. Note that the P_{stat} term has only been evaluated for $V=1m^3$, but has been applied to all volumes. This correlation has been adopted as the German, USA (up to 2013) and is the current European vent design standard.

CONTENTS

1. **Vent Area for Different Volumes: Dimensionless Terms**
2. **The use of the vessel surface area, A_s, in NFPA68.**
3. **The vessel volume effect indirectly included in the turbulence factor in NFPA68.**
4. **Vessel volume effect in dust explosion venting**
5. **The vessel volume effect in the self acceleration term in NFPA 69, critical volume for onset of self acceleration.**
6. **Review of Experimental Data as P_{red} v. $1/K_v$ or A_v/A_s for vessel of different volume**
7. **Review of Experimental Data on the Volume Effect for Gas Explosion Venting at low P_{stat} and constant K_v**
8. **Conclusions**

Vent Area for Different Volumes – Dimensional terms - 2.

Relationship of A_s to Volume, V

It may be shown that $A_s = C_2 V^{2/3}$ where C_2 is a constant that depends on the vessel shape.

For a sphere $C_2 = \pi/(\pi/6)^{2/3} = 4.84$

For a cube $C_2 = 6$

For a cylinder $C_2 = 5.54$ for L/D=1 and 5.81 for L/D=2

For a rectangular square section vessel $C_2 = 4n + 2$

Where n = the L/D ratio for a D by D cross section and for compact vessels cannot be greater than 2 so that C_2 has a maximum value of 10 for compact vessels.

If all the vessel volume effects are contained in K_v then the volume in the experiments should be irrelevant. Our 10L vented vessel was deliberately manufactured to compare the results with larger vessels in the literature to see if there was any additional volume effects.

7.2 Venting by Means of Low Inertia Vent Closures.

NFPA 68 2013

7.2.1 When $P_{red} \leq 0.5$ bar, the minimum required vent area, A_{v0}, shall be determined by Equation 7.2.1a and Equation 7.2.1b:

$$A_{v0} = \frac{A_s C}{\sqrt{P_{red}}} \qquad \textbf{(7.2.1a)}$$

7.2.1.1 The C value for flammable gases and vapors with a P_{max} value less than 9 bar and a stoichiometric (near worst case) fuel concentration no greater than about 10 percent shall be permitted to be calculated using Equation 7.2.1.1:

This comes from laminar flame venting theory

$$C = 0.0223 \lambda S_u \, \text{bar}^{1/2} \text{ for } S_u \text{ in m/s} \qquad \textbf{(7.2.1.1)}$$

In this work the turbulence factor λ will be taken as 1.

Su is the laminar burning velocity which is the same as U_L

The constant in C includes an assumed vent discharge coefficient , C_d, of 0.7. It is 0.0256 if C_d is 0.61.

CONTENTS

1. Vent Area for Different Volumes: Dimensionless Terms
2. The use of the vessel surface area, A_s, in NFPA68.
3. The vessel volume effect indirectly included in the turbulence factor in NFPA68.
4. Vessel volume effect in dust explosion venting
5. The vessel volume effect in the self acceleration term in NFPA 69, critical volume for onset of self acceleration.
6. Review of Experimental Data as P_{red} v. $1/K_v$ or A_v/A_s for vessel of different volume
7. Review of Experimental Data on the Volume Effect for Gas Explosion Venting at low P_{stat} and constant K_v
8. Conclusions

The NFPA 68 2013 venting turbulence factor λ

Four things are included:

1. Self acceleration Eq. 7.2.6.1a (follows Chippett's work)
2. Turbulence created by the vent flow – external explosion dependence Eq. 7.2.6.1c

   These effects are referred to as λ_o which is their product.
3. Obstacles (s. 7.2.6.4) Now $\lambda_1 = \lambda_o$ x f (obstacles). This function is dependent on the surface area of the obstacles – which is not a good model
4. The L/D effect up to 5 – assumption is higher L/D creates faster flames (which is correct) and included as turbulence enhancement.

7.2.6* Determination of Turbulent Flame Enhancement Factor, λ.

7.2.6.1 The baseline value, λ_0, of λ shall be calculated from Equations 7.2.6.1a through 7.2.6.1f:

Self Acc. Term

$$\varphi_1 = \begin{Bmatrix} 1, \; if \;\; \mathrm{Re}_f < 4000 \\ \left(\dfrac{\mathrm{Re}_f}{4000}\right)^{\theta}, \; if \;\; \mathrm{Re}_f \geq 4000 \end{Bmatrix} \qquad \mathbf{(7.2.6.1a)}$$

$$\mathrm{Re}_f = \frac{\rho_u S_u (D_{he}/2)}{\mu_u} \qquad \mathbf{(7.2.6.1b)}$$

External Explosion term

$$\varphi_2 = \max\left\{1, \; \beta_1 \left(\frac{\mathrm{Re}_v}{10^6}\right)^{\beta_2 \; S_u}\right\} \qquad \mathbf{(7.2.6.1c)}$$

$$\mathrm{Re}_v = \frac{\rho_u u_v (D_v/2)}{\mu_u} \qquad \mathbf{(7.2.6.1d)}$$

$$u_v = \begin{Bmatrix} \sqrt{\dfrac{2 \cdot 10^5 P_{red}}{\rho_u}}, \; if \;\; P_{red} < 0.9 \text{ bar} \\ a_u, \; if \;\; P_{red} \geq 0.9 \text{ bar} \end{Bmatrix} \qquad \mathbf{(7.2.6.1e)}$$

$$\lambda_0 = \varphi_1 \varphi_2 \qquad \mathbf{(7.2.6.1f)}$$

where:

ρ_u = mass density of unburned gas-air mixture (kg/m^3) = 1.2 for flammable gases with stoichiometric concentrations less than 5 vol%, and an initial temperature of 20°C

S_u = fundamental burning velocity of gas-air mixture (m/s)

D_{he} = the enclosure hydraulic equivalent diameter as determined in Chapter 6 (m)

μ_u = the unburned gas-air mixture dynamic velocity = 1.8×10^{-5} kg/m-s for gas concentrations less than 5 vol% at ambient temperatures

β_1 = 1.23

β_2 = 0.0487 m/s

D_v = the vent diameter as determined through iterative calculation (m)

P_{red} = the maximum pressure developed in a vented enclosure during a vented deflagration (bar-g)

a_u = the unburned gas-air mixture sound speed = 343 m/s for gas concentrations less than 5 vol% at ambient temperatures

θ = 0.39

NFPA 68 2013 p.68-16

7.2.6* Determination of Turbulent Flame Enhancement Factor, λ.

An increase in volume changes Re_f and Re_v as flame radius increases and vent diameter.

7.2.6.1 The baseline value, λ_0, of λ shall be calculated from Equations 7.2.6.1a through 7.2.6.1f:

Self Acc. Term

$$\varphi_1 = \left\{ \begin{array}{l} 1, \ if \ \ Re_f < 4000 \\ \left(\dfrac{Re_f}{4000}\right)^{\theta}, \ if \ \ Re_f \geq 4000 \end{array} \right\} \quad \text{(7.2.6.1a)}$$

$\varphi_1 \sim V^{0.13}$

$$Re_f = \frac{\rho_u S_u (D_{he}/2)}{\mu_u} \quad \text{(7.2.6.1b)}$$

External Explosion term

$$\varphi_2 = \max\left\{1, \ \beta_1 \left(\frac{Re_v}{10^6}\right)^{\beta_2 / S_u}\right\} \quad \text{(7.2.6.1c)}$$

$$Re_v = \frac{\rho_u u_v (D_v/2)}{\mu_u} \quad \text{(7.2.6.1d)}$$

Vent diameter increases with V

$\varphi_2 \sim V^{0.0075}$

$$u_v = \left\{ \begin{array}{l} \sqrt{\dfrac{2 \cdot 10^5 P_{red}}{\rho_u}}, \ if \ \ P_{red} < 0.9 \text{ bar} \\ a_u, \ if \ \ P_{red} \geq 0.9 \text{ bar} \end{array} \right\} \quad \text{(7.2.6.1e)}$$

$\lambda \sim V^{0.1375} \sim V^{1/7}$

$$\lambda_0 = \varphi_1 \varphi_2 \quad \text{(7.2.6.1f)}$$

where:

ρ_u = mass density of unburned gas-air mixture (kg/m^3) = 1.2 for flammable gases with stoichiometric concentrations less than 5 vol%, and an initial temperature of 20°C

S_u = fundamental burning velocity of gas-air mixture (m/s)

D_{he} = the enclosure hydraulic equivalent diameter as determined in Chapter 6 (m)

μ_u = the unburned gas-air mixture dynamic velocity = 1.8×10^{-5} kg/m-s for gas concentrations less than 5 vol% at ambient temperatures

β_1 = 1.23

β_2 = 0.0487 m/s

D_v = the vent diameter as determined through iterative calculation (m)

P_{red} = the maximum pressure developed in a vented enclosure during a vented deflagration (bar-g)

a_u = the unburned gas-air mixture sound speed = 343 m/s for gas concentrations less than 5 vol% at ambient temperatures

θ = 0.39

NFPA 68 2013 p.68-16

For a factor of 1000 increase in volume these two volume effects give 2.58 x the overpressure. x100 V is 1.88 This may account for some of the data above the laminar venting theory prediction.

CONTENTS

1. Vent Area for Different Volumes: Dimensionless Terms
2. The use of the vessel surface area, A_s, in NFPA68.
3. The vessel volume effect indirectly included in the turbulence factor in NFPA68.
4. Vessel volume effect in dust explosion venting
5. The vessel volume effect in the self acceleration term in NFPA 69, critical volume for onset of self acceleration.
6. Review of Experimental Data as P_{red} v. $1/K_v$ or A_v/A_s for vessel of different volume
7. Review of Experimental Data on the Volume Effect for Gas Explosion Venting at low P_{stat} and constant K_v
8. Conclusions

Dust explosion venting correlation of Bartknecht - 1

The experimental data for vented dust explosions that was presented in the last section, was correlated by Bartknecht in a similar way to that he did for gas explosions.

For a P_{stat} of 100 mb the correlation was:

$$A_v = 3.264\text{x}10^{-5} P_{red}^{-0.569} P_m K_{st} V^{0.753}$$

This was valid for P_{red} < 2 bar and V < 1000 m^3 and K_{st}<800

Note that the volume exponent is not 2/3 but is 0.753, this was demonstrated in the experimental results.

This equation can be converted into that using K_v ($V^{2/3}/A_v$)

$$1/K_v = 3.264 \times 10^{-5} P_{red}^{-0.569} P_m K_{st} V^{0.086}$$

Note $V^{0.086} \sim V^{1/12}$

The additional volume term implies larger overpressures for larger volume vessels – as has been found for gas explosions. It may be that the self acceleration of flames due to cellular structure might apply to dust explosions.

CONTENTS

1. **Vent Area for Different Volumes: Dimensionless Terms**
2. **The use of the vessel surface area, A_s, in NFPA68.**
3. **The vessel volume effect indirectly included in the turbulence factor in NFPA68.**
4. **Vessel volume effect in dust explosion venting**
5. **The vessel volume effect in the self acceleration term in NFPA 69, critical volume for onset of self acceleration.**
6. **Review of Experimental Data as P_{red} v. $1/K_v$ or A_v/A_s for vessel of different volume**
7. **Review of Experimental Data on the Volume Effect for Gas Explosion Venting at low P_{stat} and constant K_v**
8. **Conclusions**

The critical diameter of the flame for the onset of self acceleration is quite small according to the NFPA68 correlation. Eq. 7.2.6.1a.

Self acceleration occurs if $Re_j > 4000$

$Re_j = U_L (D/2)/ \upsilon$

$D = 2 Re_j \upsilon / U_L$ where υ = kinematic viscosity = 15.6×10^{-6} air

For methane $U_L = 0.42$ this gives $D_{crit} = 0.297$m

This is a vessel spherical volume of 0.0137 m^3 ~ 14L

Our 10L vessel was deliberately chosen so that self acceleration should not occur.

A 13.7 m^3 vessel is 1000 times this volume and the $V^{0.1375}$ dependence gives 2.58 for λ.

A 1370 m^3 volume is a 100,000 times this volume and $\lambda = 4.9$

The problem with the flame self acceleration term in NFPA 68 (2013) is that there is no limit set on the self acceleration.

All the evidence from large scale tests is that self acceleration ceases after about 6m diameter or 116m^3.

Also apart from the burning velocity term in the critical Re for self acceleration, there is no reactivity term in the self acceleration equation. This means that all fuels accelerate the same, which is known not to be the case.

The Θ exponent is set constant at 0.39 and Chippett's work had this at 0.4 for propane and 0.25 for methane. There would be a higher value for hydrogen.

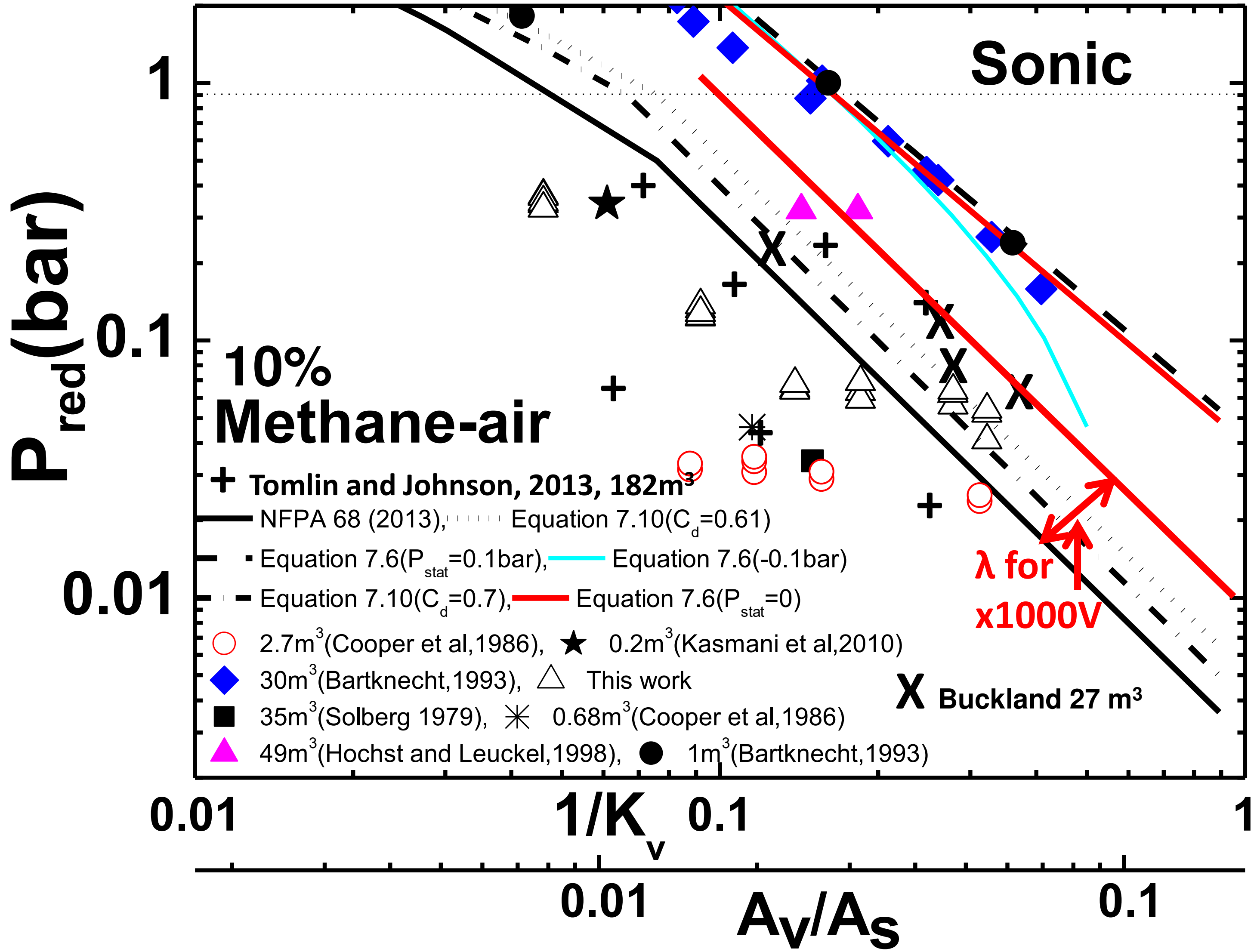
CONTENTS

1. **Vent Area for Different Volumes: Dimensionless Terms**
2. **The use of the vessel surface area, A_s, in NFPA68.**
3. **The vessel volume effect indirectly included in the turbulence factor in NFPA68.**
4. **Vessel volume effect in dust explosion venting**
5. **The vessel volume effect in the self acceleration term in NFPA 69, critical volume for onset of self acceleration.**
6. **Review of Experimental Data as P_{red} v. $1/K_v$ or A_v/A_s for vessel of different volume**
7. **Review of Experimental Data on the Volume Effect for Gas Explosion Venting at low P_{stat} and constant K_v**
8. **Conclusions**

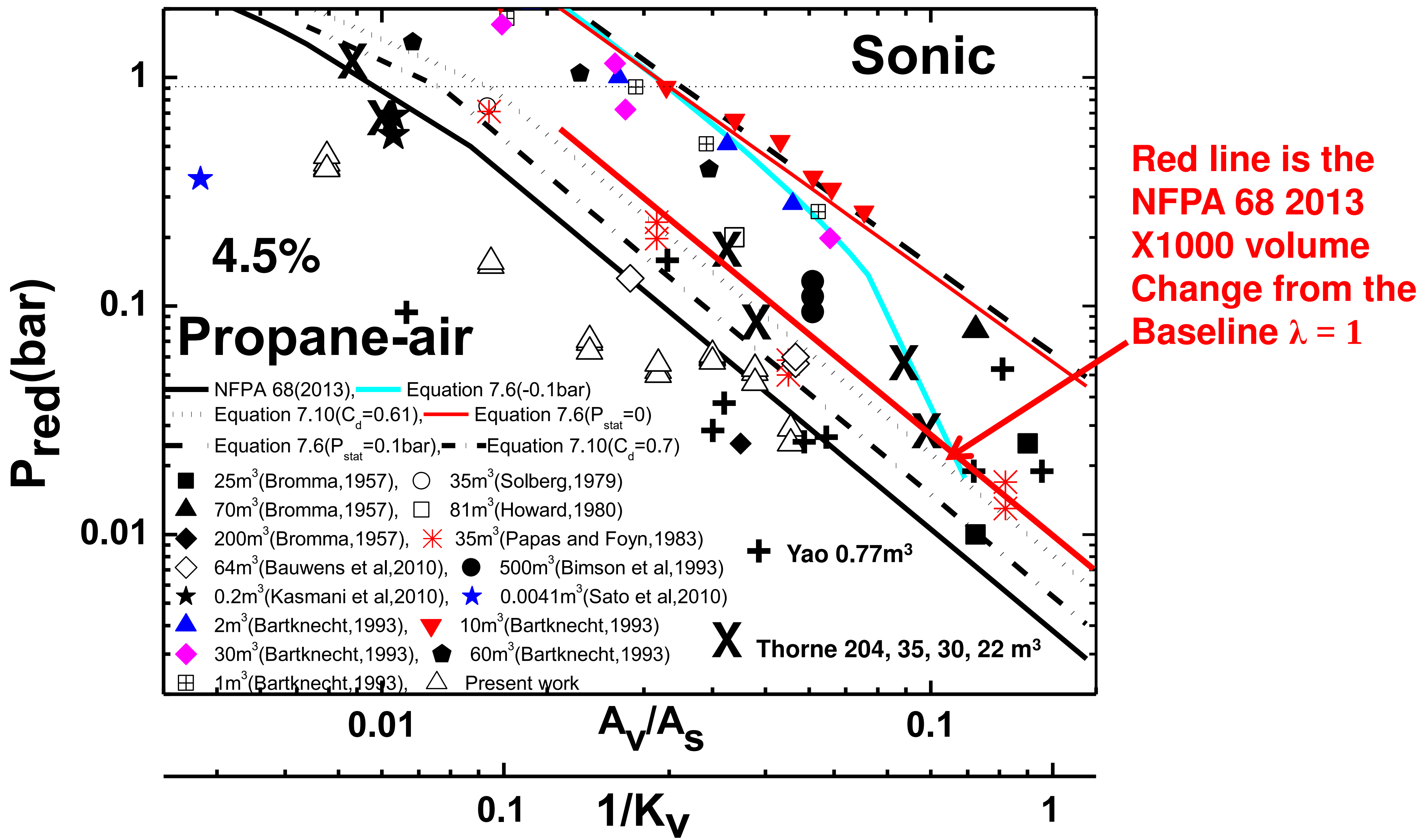
This work aims to review published data on vented explosions to see if there is evidence for a strong volume effect at constant K_v.

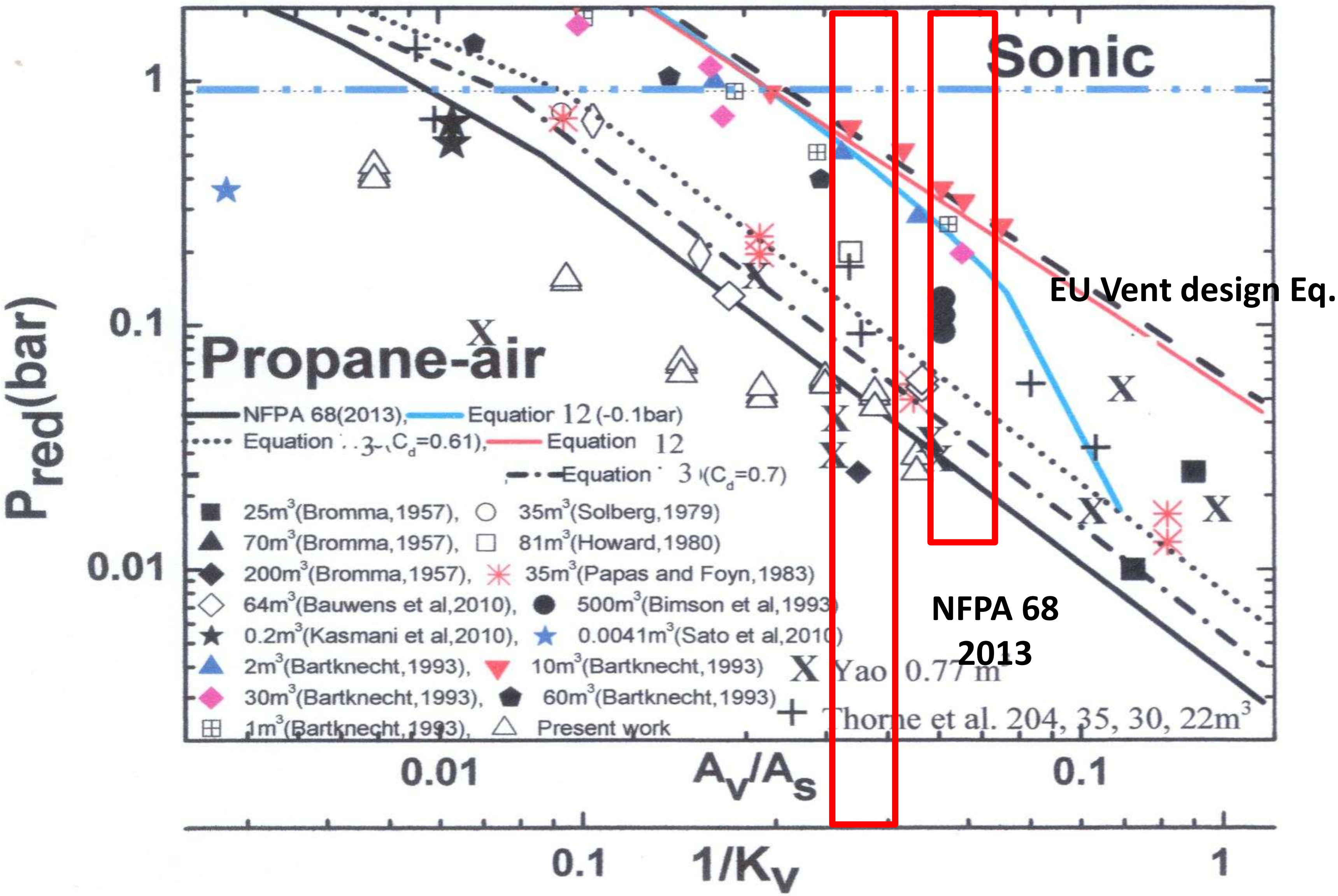
The work uses the data for P_{red} for the lowest static pressure studied in each publication. Where possible free venting data was used.

In the European guidance on gas venting there is no other volume term, so that for the same K_v all vessels should have the same P_{red}



P_{red} as a function of $1/K_v$ and A_v/A_s (for a cube). Comparison with the laminar flame theory Eq. 3, NFPA 68(2013) Eq. 4 and EN14994:2007. Eq. 12 with Bartknecht's and other literature experimental data and with the present results of a 20L vented vessel with L/D = 2.8 and end ignition.

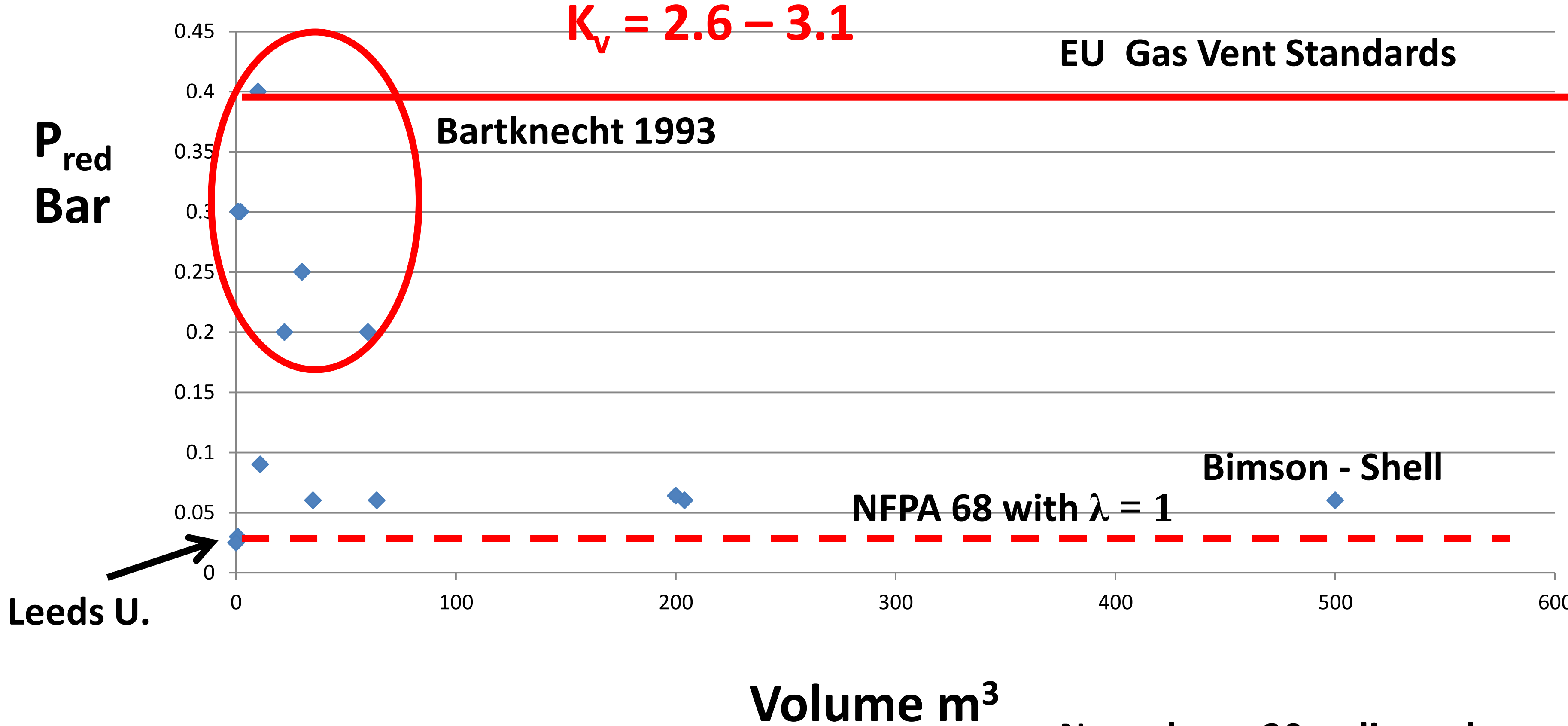

Sonic
4.5%
Propane-air
P_{red}(bar)
1
0.1
0.01
A_V/A_S
0.01
0.1
$1/K_V$
0.1
1
NFPA 68(2013), Equation 7.6(-0.1bar)
Equation 7.10(C_d=0.61), Equation 7.6(P_{stat}=0)
Equation 7.6(P_{stat}=0.1bar), Equation 7.10(C_d=0.7)
25m³(Bromma,1957), 35m³(Solberg,1979)
70m³(Bromma,1957), 81m³(Howard,1980)
200m³(Bromma,1957), 35m³(Papas and Foyn,1983)
64m³(Bauwens et al,2010), 500m³(Bimson et al,1993)
0.2m³(Kasmani et al,2010), 0.0041m³(Sato et al,2010)
2m³(Bartknecht,1993), 10m³(Bartknecht,1993)
30m³(Bartknecht,1993), 60m³(Bartknecht,1993)
1m³(Bartknecht,1993), Present work
Yao 0.77m³
Thorne 204, 35, 30, 22 m³
Red line is the NFPA 68 2013 X1000 volume Change from the Baseline λ = 1


Sonic
Propane-air
EU Vent design Eq.
NFPA 68 2013
NFPA 68(2013), Equation 12 (-0.1bar)
Equation 3 (C_d=0.61), Equation 12
Equation 3 (C_d=0.7)
25m³(Bromma,1957), 35m³(Solberg,1979)
70m³(Bromma,1957), 81m³(Howard,1980)
200m³(Bromma,1957), 35m³(Papas and Foyn,1983)
64m³(Bauwens et al,2010), 500m³(Bimson et al,1993)
0.2m³(Kasmani et al,2010), 0.0041m³(Sato et al,2010)
2m³(Bartknecht,1993), 10m³(Bartknecht,1993)
30m³(Bartknecht,1993), 60m³(Bartknecht,1993)
1m³(Bartknecht,1993), Present work
X Yao 0.77 m³
+ Thorne et al. 204, 35, 30, 22m³
P_red(bar)
A_V/A_S
1/K_V
1
0.1
0.01
0.01
0.1
0.1
1

CONTENTS

1. **Vent Area for Different Volumes: Dimensionless Terms**
2. **The use of the vessel surface area, A_s, in NFPA68.**
3. **The vessel volume effect indirectly included in the turbulence factor in NFPA68.**
4. **Vessel volume effect in dust explosion venting**
5. **The vessel volume effect in the self acceleration term in NFPA 69, critical volume for onset of self acceleration.**
6. **Review of Experimental Data as P_{red} v. $1/K_v$ or A_v/A_s for vessel of different volume**
7. **Review of Experimental Data on the Volume Effect for Gas Explosion Venting at low P_{stat} and constant K_v**
8. **Conclusions**

Propane – Air 4 – 4.5% Low P_{stat}



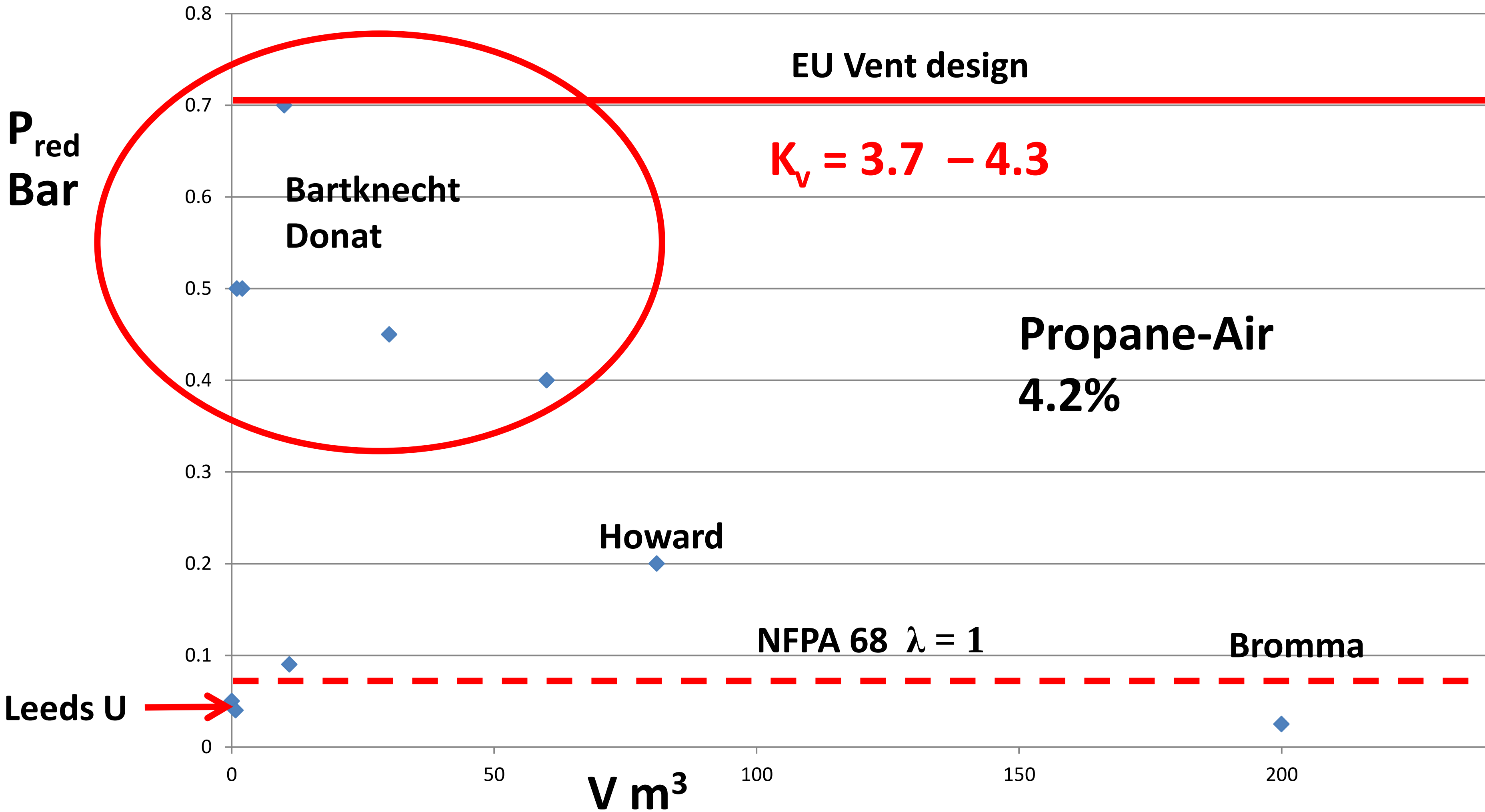
Note that a 30m dia tank 10m high is 7,070 m^3

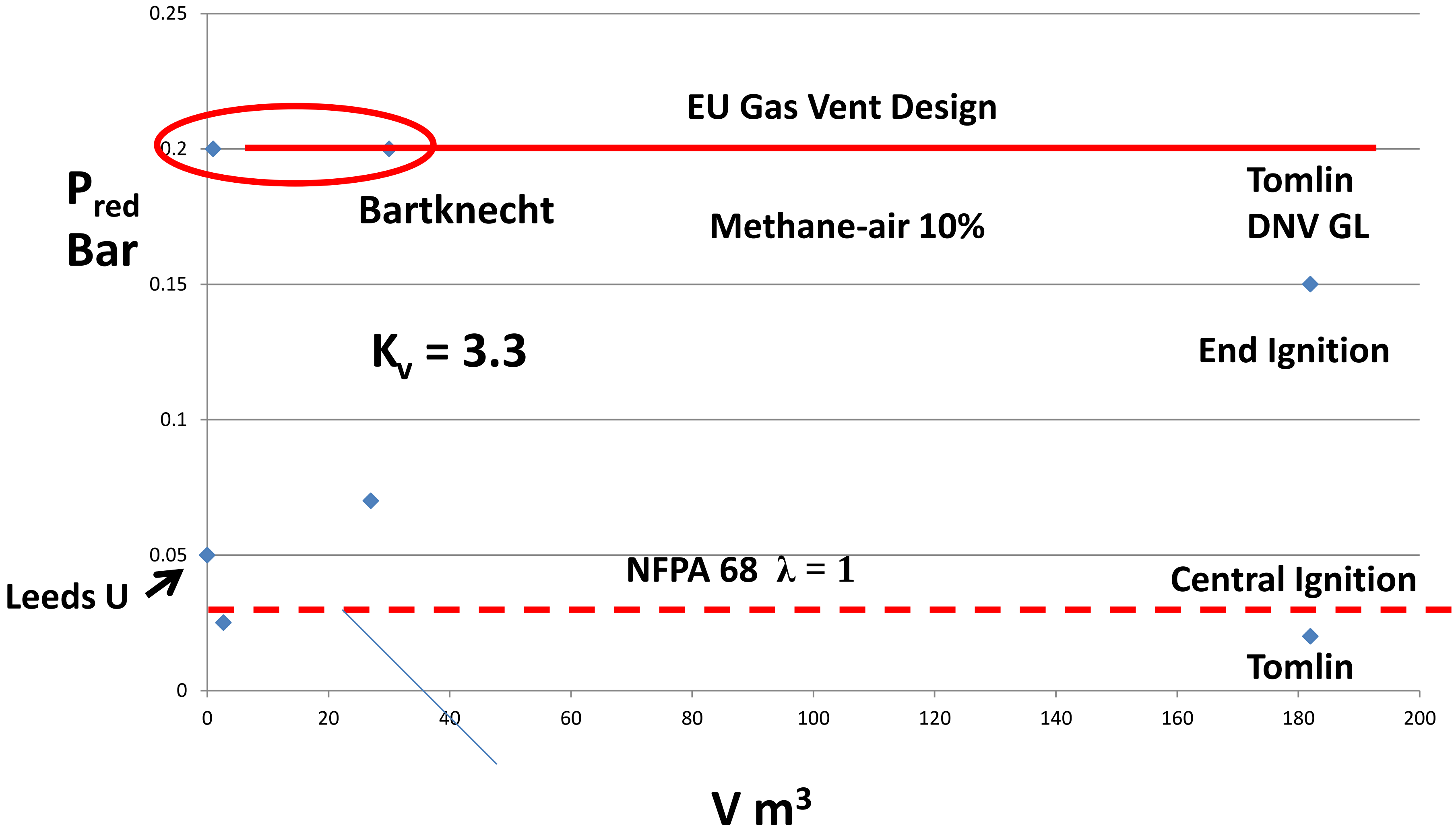
14 data points – 5 from Bartknecht

Vent design standards are supposed to be valid to 1000 m^3 but no validation that they are.

The Influence of Vessel Volume at Constant K_v for Vented Gas Explosions

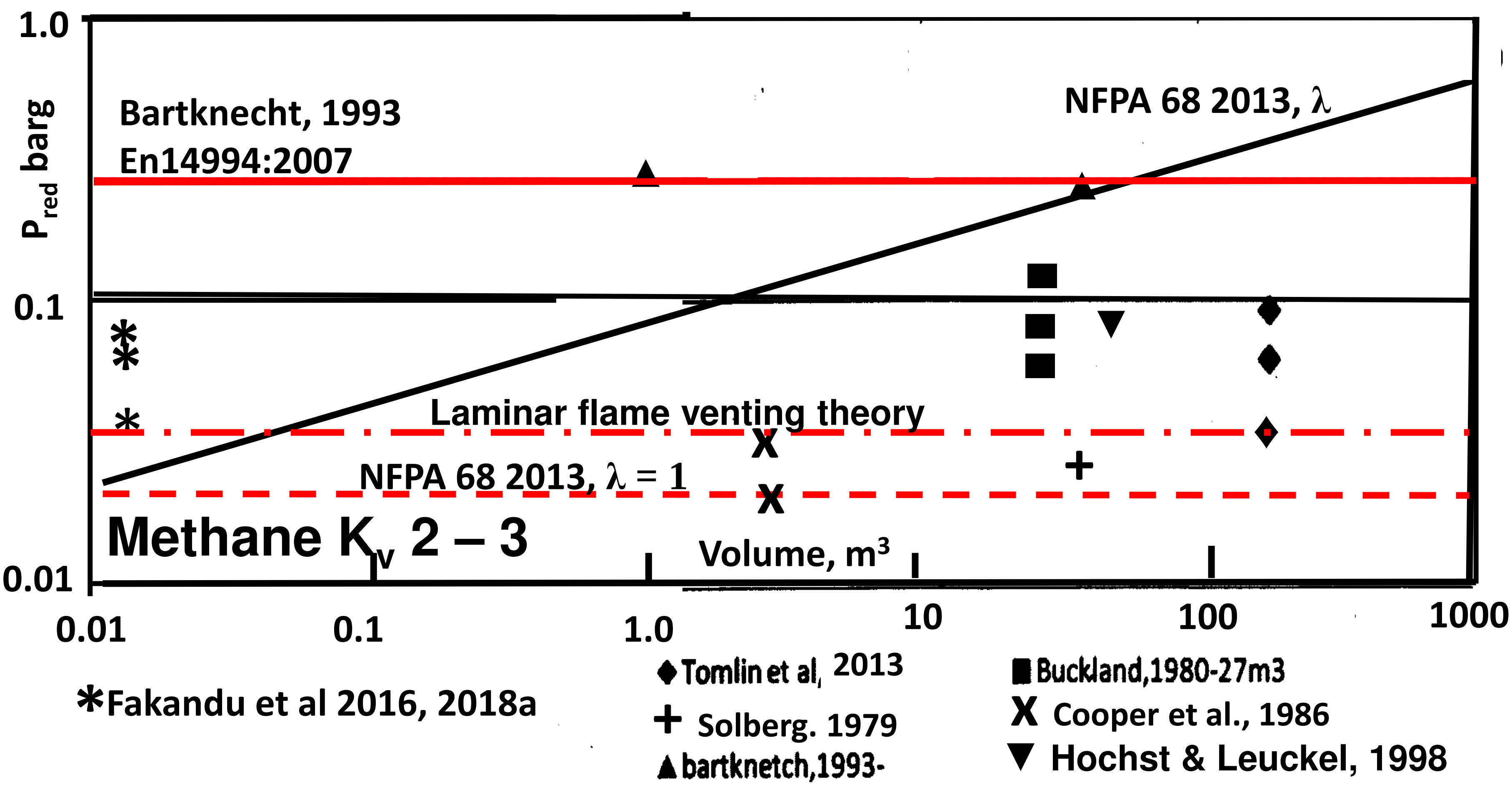
Fakandu, B., Tomlin, G., Phylaktou, H.N. , Andrews, G.E. , **U. Leeds**




EU Gas Vent Design
Bartknecht
Methane-air 10%
Tomlin
DNV GL
End Ignition
K_v = 3.3
P_{red} Bar
NFPA 68 λ = 1
Central Ignition
Leeds U
Tomlin
V m³
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100
120
140
160
180
200

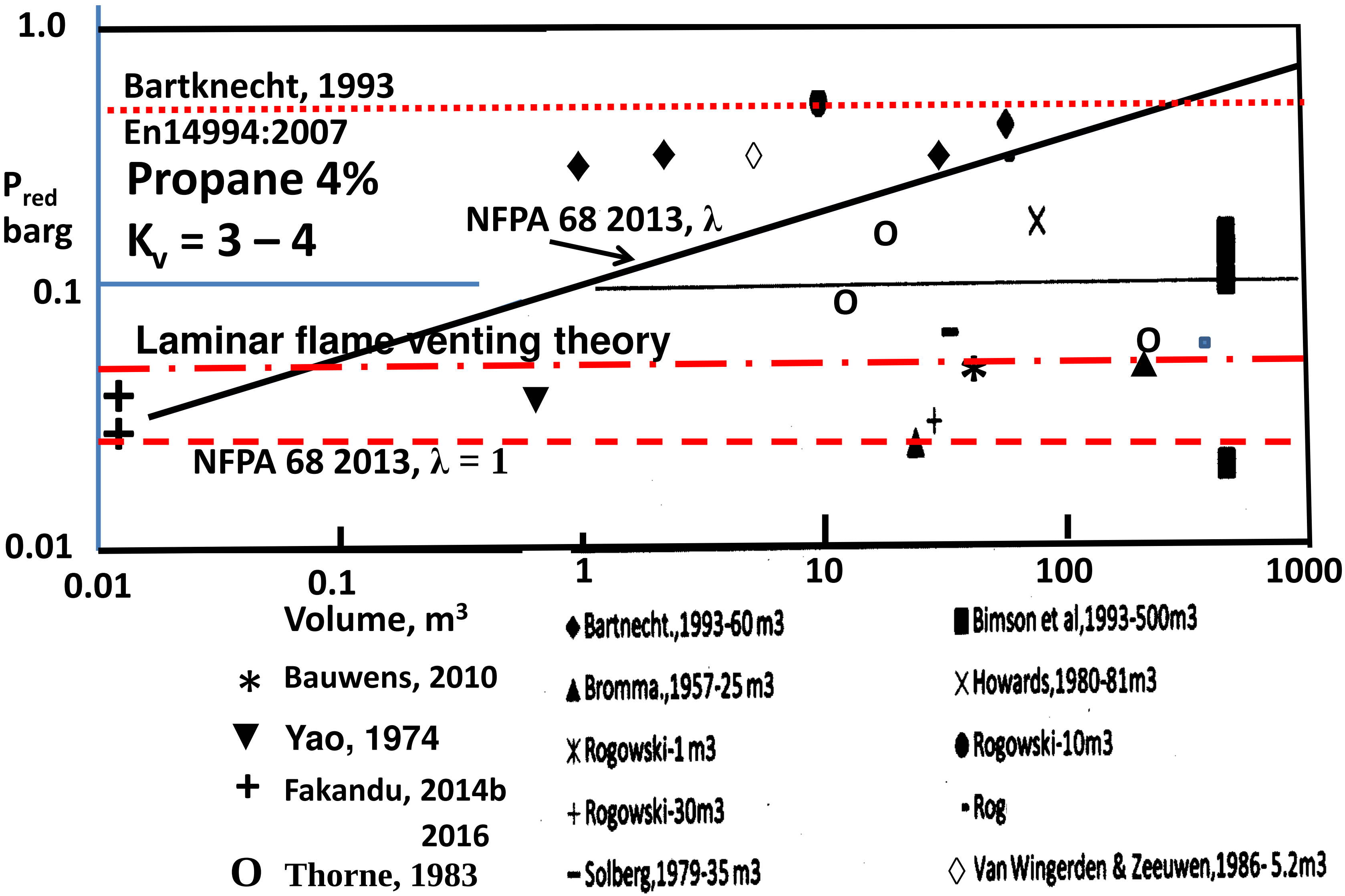
The Influence of Vessel Volume at Constant K_v for Vented Gas Explosions

Fakandu, B., Tomlin, G., Phylaktou, H.N. , Andrews, G.E. , **U. Leeds**



The Influence of Vessel Volume at Constant K_v for Vented Gas Explosions

Fakandu, B., Tomlin, G., Phylaktou, H.N. , Andrews, G.E. , **U. Leeds**



CONTENTS

1. **Vent Area for Different Volumes: Dimensionless Terms**
2. **The use of the vessel surface area, A_s, in NFPA68.**
3. **The vessel volume effect indirectly included in the turbulence factor in NFPA68.**
4. **Vessel volume effect in dust explosion venting**
5. **The vessel volume effect in the self acceleration term in NFPA 69, critical volume for onset of self acceleration.**
6. **Review of Experimental Data as P_{red} v. $1/K_v$ or A_v/A_s for vessel of different volume**
7. **Review of Experimental Data on the Volume Effect for Gas Explosion Venting at low P_{stat} and constant K_v**
8. **Conclusions**

Conclusions on the influence of volume.

The influence of vessel volume is low and the NFPA 68 2013 λ corrections for cellular flame self acceleration of flames and external explosions give far to high an influence of vessel volume which is not supported by experiments.
The NFPA68 (2013) gas venting design procedures have a volume dependence from the self acceleration term that is not supported by experimental data.

Bartknecht's results are abnormal relative to other results with larger volumes.

Bartknecht's high values for P_{red} are NOT due to his use of relatively large volumes in his experiments, as experiments in larger volumes do not find these high P_{red}.