Analysis of API-99 Flow Rate Testgroup Data

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1 Abstract

The API 2000[1] committee decided that the complaints by some venting device manufacturers that published and certified flow curves by some vendors were not accurate motivated the committee to charter a Flow Certification Taskgroup[2] to investigate this issue. The taskgroup decided to perform testing, but it quickly became apparent that there were disagreements as to the effect of using the testing protocols in the 5th versus the 7th edition of API 2000. Apparently about half of the manufacturers follow the 5th edition testing protocol specified in API 2000 and the other half use the 7th edition version which is substantially different. As a result, the taskgroup decided to allow usage of the test rigs that vendors currently use but to initially limit flow testing only the flow nozzle used to mount the venting device. The test specified that a set of flow nozzles be manufactured for this purpose and that one by one each of the participating vendors would flow test the nozzle according to their testing protocols. The result was a wide scatter of flow results which means that no testing of the actual PV valves should be undertaken until the testing protocol can ensure that flow rates cluster within acceptable limits. The error in flow measurement is not a result of the testing rig (5th or 7th edition versions) necessarily. Unfortunately, the error results partly from the vendor testing methods as well as possibly the testing rig version. Because replicate measurements were not made for each flow test, the error resulting from vendor and test rig is confounded and cannot be determined without further testing according to a modified testing protocol. This work is being submitted to API for further handling. Details of the analysis are shown below. In addition, the anonymized datasets, the analysis, and programming used to provide these results is available at this link https://github.com/rbitip/Public-API-2000-Flow-Certification-Testing.

2

3 Summary

3.1 A Cooperative study of in-house flow rate test rigs.

Six vendors participated in a comparative study of flow rate measurements executed on their in-house API-2000 test rigs. Vendors were tasked with measuring flow rates through three different sizes of the pressure relief nozzle (labeled “pipe to vessel” in Figure 1), at five different inlet pressures. The purpose was to determine if vendor’s in-house test rigs agree with each other.

[1] API Standard 2000, 7th edition, March 2014 “Venting Atmospheric and Low-Pressure Storage Tanks”
[2] PEMyers (phil@pemyconsulting.com) chairs this taskgroup. The TG is made up of PV venting valve manufacturers, owners, and users as well as consultants. The taskgroup reports to the API 2000 committee.

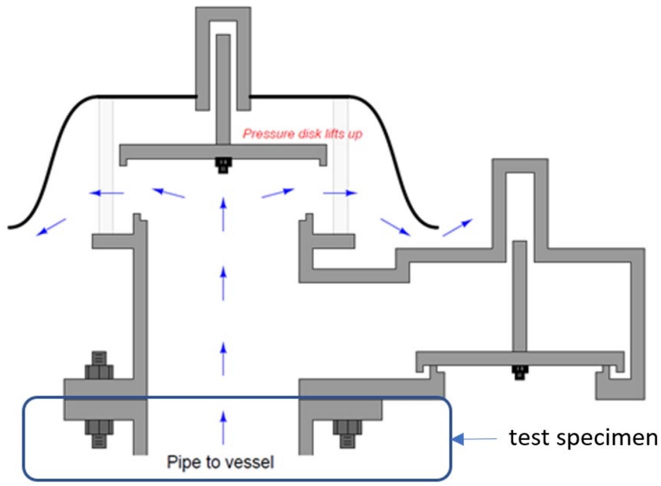

Figure 1. Pipe to vessel nozzle.

Four vendors submitted complete data. After analyzing these data, we found that flow rates measured by the four vendors under identical conditions of inlet pressure and orifice diameter differ by -8.7% to 6.2% (Table 4 and Figure 2). **Disparities of this magnitude cast doubt on the reliability of vendors' sizing tables.**

3.2 Reference Standards

Other industries, such as pharmacology and immunoassay, rely upon **reference standards** to ensure comparability of measurements made at different test facilities. For example, the United States Pharmacopeial Convention[3] (USP), a nonprofit organization,

> *" … currently offers more than 3,500 Reference Standards—highly characterized specimens [**reference standards**] of drug substances, excipients, food ingredients, impurities, degradation products, dietary supplements, compendial reagents and performance calibrators. USP Reference Standards are specified for use in conducting official USP–NF tests and assays. USP also provides Reference Standards specified in the Food Chemicals Codex as well as authentic substances—high-quality chemical samples—as a service to analytical, clinical, pharmaceutical and research laboratories."*

In the context of pressure/vacuum relief valves, reference standards would be several sizes of nozzles with precise and accurate, directly measured[4] mass flow rates over a range of inlet pressures. A vendor would order replicas of the reference standards to test on their own test rig. Discrepancies would be dealt with by the vendor tuning their test rig , tightening their measurement protocol, and/or developing correction factors.

[3] https://en.wikipedia.org/wiki/United_States_Pharmacopeia

[4] The most precise and accurate method of measuring some quantity is informally called a *Gold Standard*.

4 Analysis of Vendor Data

Each vendor received three nozzles with nominal outer diameter (OD) 2", 6", and 10", respectively. Each vendor was asked to measure the inner diameter (ID) at three equal angles and report the average, and to measure flow rates (SCFH) for each specimen, with the vessel pressurized or partially evacuated, to nominal pressure differences of 1, 2, 3, 4, and 5 inches of water column (in wc). Thus, each vendor was expected to report 30 flow rates (3 diameters x 5 pressures x 2 modes[5]); Table 1 shows raw sample data[6] from vendor "E".
None of the six vendors submitted complete data; however, four vendors (A, B, E, and F) gave us complete data on pressures 2, 3, 4, and 5. So, the data set we analyzed contained 96 observations (4 vendors x 3 diameters x 4 pressures x 2 modes): 48 in pressure mode and 48 in vacuum mode.

pipe diameter (in)		pressure diff. (iwc)		Flow rate (SCFH)	
OD	avg ID	nominal	actual	pressure	vacuum
2	1.346	1	1.02	2072	2151
2	1.346	2	2.02	2882	3029
2	1.346	3	3.01	3531	3497
2	1.346	4	4.01	4068	3989
2	1.346	5	5.02	4556	4555
6	3.992	1	1.01	14721	14907
6	3.992	2	2.07	20848	20346
6	3.992	3	3.01	24891	25035
6	3.992	4	4.10	29264	29897
6	3.992	5	5.03	32349	33311
10	6.693	1	1.01	39625	41080
10	6.693	2	2.02	55433	57102
10	6.693	3	3.04	67233	70215
10	6.693	4	4.05	77759	81238
10	6.693	5	5.03	87928	92122

Table 1. Raw Data from Vendor "E"

5 Pressure Mode Results

5.1 Comparison of Vendors

We can determine the relative precision of the four vendors by analyzing how far each one deviates from the average; however, however without reference standards[7] we cannot determine their accuracy. Of course, if the

[5] Pressure or vacuum.
[6] For complete data see github For complete data see https://github.com/rbitip/Public-API-2000-Flow-Certification-Testing
[7] A gold standard is a *method* of measurement that is certified to produce accurate results by a standards-setting body; it is typically too expensive to use in routine measurement. An example would be directly measured mass flow rate. *Reference*

vendors are significantly different then at least one of them must be inaccurate. So, we are in the position of determining whether the vendors agree with one another (within the margin of statistical error), but we cannot say which of them deviate significantly from true, gold standard, flow rates.

We analyzed the logarithm of flow rate for two reasons. First, theoretical flow rate is the product of orifice area and a complicated expression involving inlet and outlet pressure; taking the log makes these two terms additive and improves normality of the data. Second, flow rate varies by several orders of magnitude.

5.2 Analysis of Variance (ANOVA)

This analysis partitions the total variation of the 48 pressure-mode flow rates into "sums of squares" that indicate how much of the total variation is explained by each factor in the experiment. The "*p*-value" is generally described as the probability of getting a sum of squares this large if the factor in question actually has no influence on flow rate; a *p*-value smaller than 0.05 is conventionally taken as an indication that the factor is "statistically significant": it really has an influence. Significant *p*-values are in **red boldface**.

The message of Table 2 is that ***vendor bias is real and is not strongly modulated by diameter or pressure***. In the next section we show graphically what this means.

Factor: D = nominal OD
P = nominal pressure difference
V = vendor

	Factor	df	Sum of Squares	Mean of Squares	F value	*p*-value
Consensus Flow Rate	D	2	72.89353	36.44676	177681.6	**0.0000**
	P	3	1.40888	0.469628	2289.481	**0.0000**
	D:P	6	0.00258	0.000430	2.097665	0.1043
Vendor bias	V	3	0.18047	0.060157	293.2692	**0.0000**
Noise	D:V	6	0.00273	0.000455	2.217552	0.0890
	P:V	9	0.00264	0.000293	1.427969	0.2481
	Residual (pure error)	18	0.00369	0.000205	0.000205	

Table 2. ANOVA table for Pressure Mode

5.3 Graphical Analysis of Vendor Precision

Consensus flow rate is the antilog of the average log(flowrate) over vendors at each combination of diameter and pressure; i.e., consensus flow rates are geometric means[8]. A gold standard would have the same format as Table 3 but would be based on high precision mass flow rate measurements. In this paper we compare individual vendors to the consensus flow rates in Table 3.

As shown in Table 2, the biggest influence on consensus flow rate is orifice diameter (factor D), followed by pressure (factor P) as would be expected.

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standards are identical replicas of a *thing*, for example a 6" nozzle, that has been measured using the gold standard method.

[8] Geometric mean of four numbers: $gm = \left(A \cdot B \cdot E \cdot F\right)^{1/4};\ \ln\left(gm\right) = \left[\ln\left(A\right) + \ln\left(B\right) + \ln\left(E\right) + \ln\left(F\right)\right]/4$

D:P "interaction" means lack of parallelism between the flow profiles in Table 3. In the pressure condition it is insignificant but shows up as a barely perceptibly steeper slope of the line segment between ordinates 2 and 3 for the 10-inch orifice and the corresponding slopes for 2 and 6 inch orifices.

nominal		consensus		confidence limits	
Diam	Press	SCFH	sigma	5%	95%
2	2	2982	21	2937	3027
2	3	3603	26	3548	3657
2	4	4153	30	4091	4216
2	5	4602	33	4532	4671
6	2	21502	154	21179	21826
6	3	25982	186	25591	26373
6	4	30322	217	29866	30778
6	5	34298	246	33782	34814
10	2	56304	403	55457	57151
10	3	69799	500	68749	70849
10	4	80675	578	79461	81889
10	5	90329	647	88970	91688

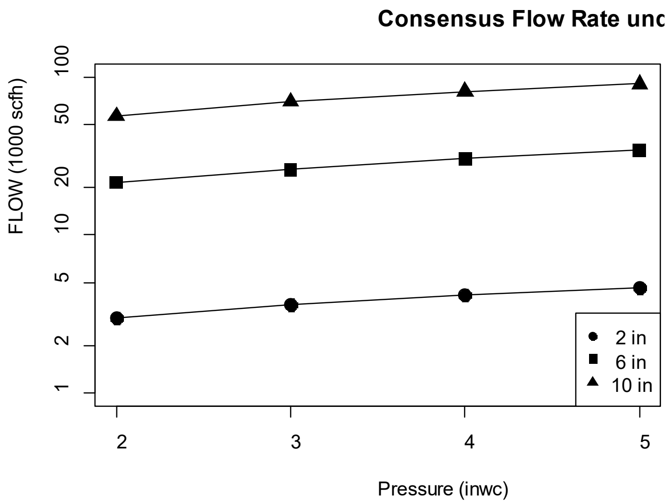

Table 3. Consensus Flow Rates.

5.4 Deviations from Consensus

Factor V (vendors) is highly significant in the ANOVA table, which indicates that some vendors are consistently higher and some consistently lower than average.
Average percent vendor deviations from consensus, "vendor bias" for short, are shown in Table 4. Vendors A and B have barely overlapping margins of error and vendors E and F are widely separated from each other and from A and B. The differences among vendors are not just statistically *significant*, they are practically *important*[9].

5.5 Impact on Sizing Calculations

For example, vendor "A" thinks that the true flow rate is 16 percent[10] higher than does vendor "F" and would therefore recommend 16% fewer vents than vendor "F" would to achieve the same discharge rate in a tank being designed. Following A's advice could create a risk of tank failure if F is correct.
Conversely vender "F" thinks that the true flow rate is 14 percent[11] lower than does vendor A and would therefore recommend 14% fewer vents than vendor "A". Following F's advice would cause unnecessary expense if A is correct.

[9] "Statistically significant" means "beyond the margin of error";
"important" means "needs to be taken into account to avoid negative consequences."
[10] (1+.0672)/(1-.0817) -1 = 0.162
[11] (1-.0817)/(1+.0672) -1 = -0.140

	Percent deviation from CFR[12]		
		Margin of error	
Vendor	estimate	lower	upper
A	6.72	5.92	7.52
B	5.23	4.44	6.03
E	-3.03	-3.76	-2.30
F	-8.17	-8.86	-7.48

Table 4. Vendor bias (percent).

5.6 Noise Components

Total noise, shown in Figure 2, is measured flow rate minus CFR and vendor bias. Total noise has three components, vendor by diameter bias (V:D), vendor by pressure bias (V:P), and pure error (residual). The horizontal axis shows nominal orifice diameter (major ticks) and nominal pressure difference (minor ticks[13]); solid symbols are noise; dotted lines are vendor bias.
Vendor bias stands out above the noise (that's what it means to be statistically significant).

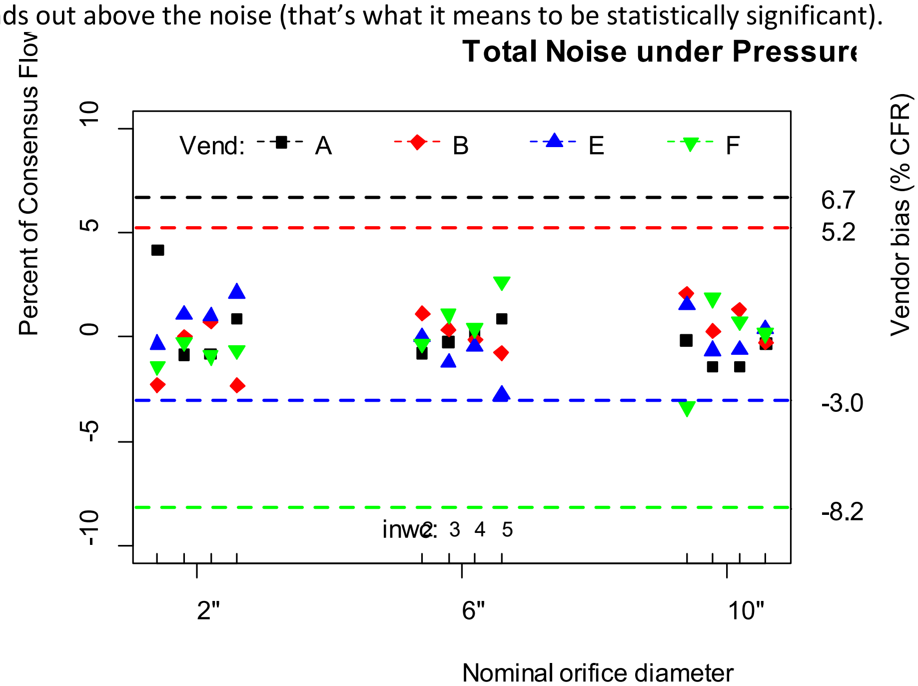

Figure 2. Total Noise

[12] Consensus Flow Rate
[13] As inches of water column (inwc).

In ANOVA Table 2, noise is broken out as vendor bias by orifice diameter (V:D), vendor bias by pressure difference (V:P) and pure error. V:P is indistinguishable from pure error and V:D is near significance.
In Figure 2, V:D shows up as different patterns for different vendors, “up-down-up” for vendors A and E, “down up down” for vendors B and F but the pattern is not statistically significant and is unlikely to be reproducible. In any case V:D is very small, amounting to less than one percent of consensus flow rate.

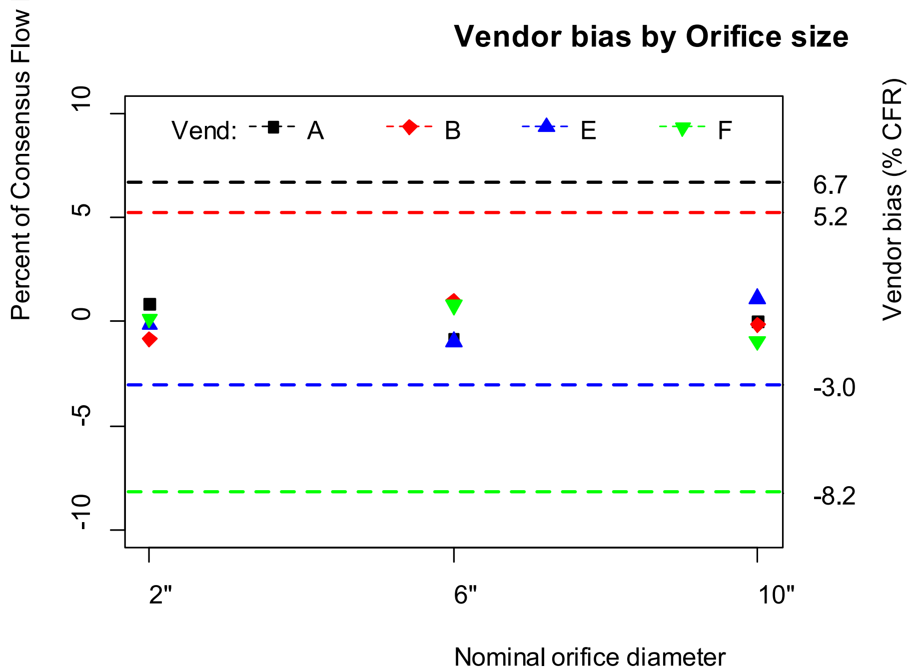

Figure 3. Vender bias by Orifice Diameter

Pure error, plotted in Figure 3, is the chaotic “leftovers”; amounting to about one percent of consensus flow rate. Yes, it is tempting to speculate about the behavior of vendor “E” but verifying it statistically would require each vendor to have run the experiment twice. In 20:20 hindsight, that should have been part of the experimental design.

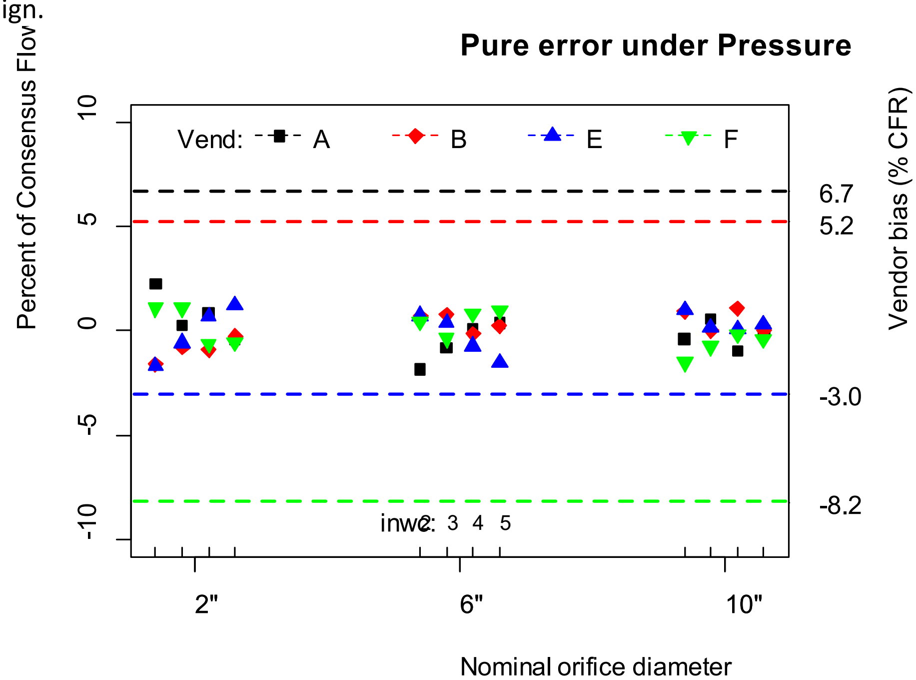

Figure 4. Pure Error

7 Vacuum Mode Results

We'll present the results in the same format as above, commenting only where vacuum differs from pressure.

7.1 Analysis of Variance (ANOVA)

Vendor bias by orifice diameter (D:V) is highly significant, which it wasn't under pressure.

		df	Sum Sq	Mean Sq	F value	*p*-value
Consensus Flow Rate	D	2	75.6361	37.8180	56737.2793	**0.0000**
	P	3	1.3427	0.4476	671.4939	**0.0000**
	D:P	6	0.0050	0.0008	1.2519	0.3272
Vendor bias	V	3	0.2827	0.0942	141.3580	**0.0000**
Noise	D:V	6	0.0391	0.0065	9.7752	**0.0001**
	P:V	9	0.0048	0.0005	0.7987	0.6225
	Residual	18	0.0120	0.0007		

7.2 Consensus Flow Rates.

nominal		consensus		confidence limits	
Diam	Press	SCFH	sigma	5%	95%
2	2	2882	37	2804	2961
2	3	3446	44	3352	3539
2	4	3907	50	3801	4013
2	5	4417	57	4297	4537
6	2	21845	282	21253	22438
6	3	25754	332	25055	26452
6	4	30234	390	29414	31054
6	5	33860	437	32942	34778
10	2	56813	733	55273	58354
10	3	70026	904	68127	71925
10	4	81212	1048	79009	83414
10	5	91718	1184	89231	94205

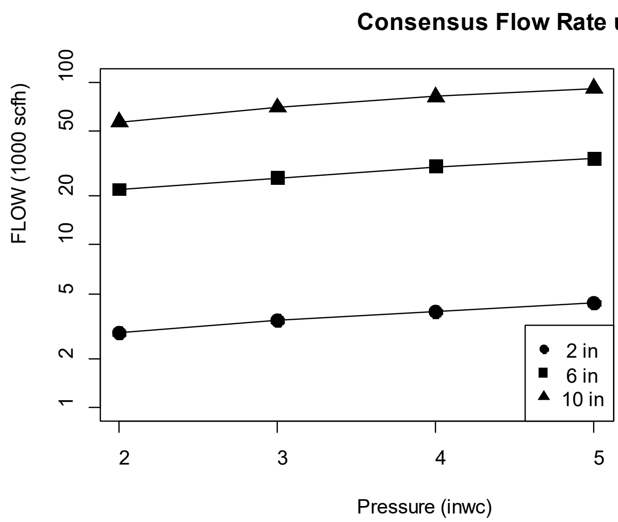

Table 5. Consensus Flow Rates under Vacuum

7.2.1 Pressure vs Vacuum

Pressure and vacuum CFR's are virtually the same[14] for 6" and 10" orifices; however, for the 2" orifice, flow rate averages 4.6% higher under pressure than under vacuum. The difference is statistically significant[15] for reasons yet to be explained.

[14] Average % difference =-0.31.
[15] 2" vs (6" & 10"): t = 78.3, df = 10, *p* = 0.000,03

nominal		Consensus flow rate		
Diam	Press	Pressure	Vacuum	% Difference
2	2	2982	2882	3.47
2	3	3603	3446	4.56
2	4	4153	3907	6.30
2	5	4602	4417	4.19
6	2	21502	21845	-1.57
6	3	25982	25754	0.89
6	4	30322	30234	0.29
6	5	34298	33860	1.29
10	2	56304	56813	-0.90
10	3	69799	70026	-0.32
10	4	80675	81212	-0.66
10	5	90329	91718	-1.51

Table 6. Consensus Pressure vs Vacuum

7.2.2 Deviation of Vendors from consensus flow rates

The pattern is different from the pressure condition. For vacuum, “A” is significantly higher, “B” and “E” are indistinguishable, and “F” is significantly lower.

	Percent deviation from CFR		
		Margin of error	
Vendor	estimate	lower	upper
A	11.17	9.68	12.69
B	0.49	-0.86	1.86
E	0.01	-1.34	1.38
F	-10.50	-11.71	-9.28

Table 7. Vendor bias under Vacuum

7.3 Noise Components

Total noise includes measurement error plus second and third order vendor effects. However, some of the noise can be attributed to Vendor Bias by Orifice diameter (V:D).

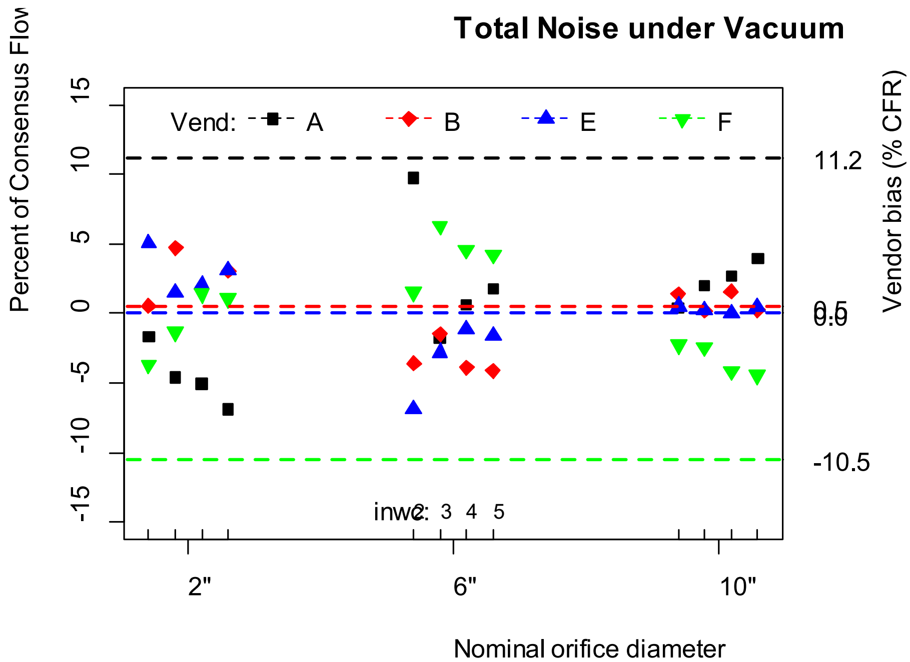

Figure 5. Total Noise under Vacuum

Total noise can be broken into vendor bias by orifice size and pure error.
Vendor bias by orifice size (V:D) is statistically significant in vacuum mode.

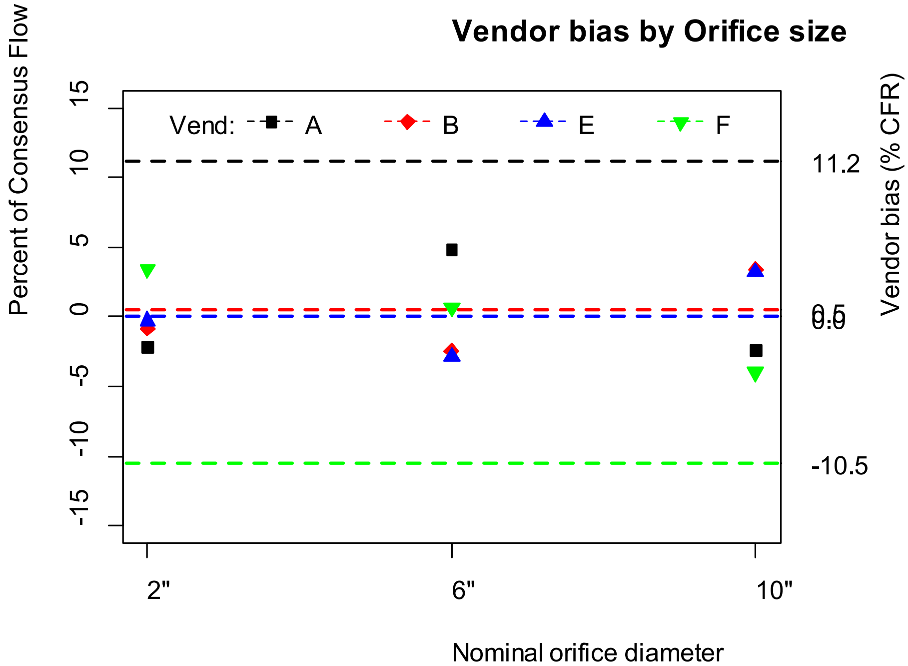

Figure 6. Vendor bias by orifice size under vacuum

After subtracting (V:D) Pure Error is small compared to vendor bias.

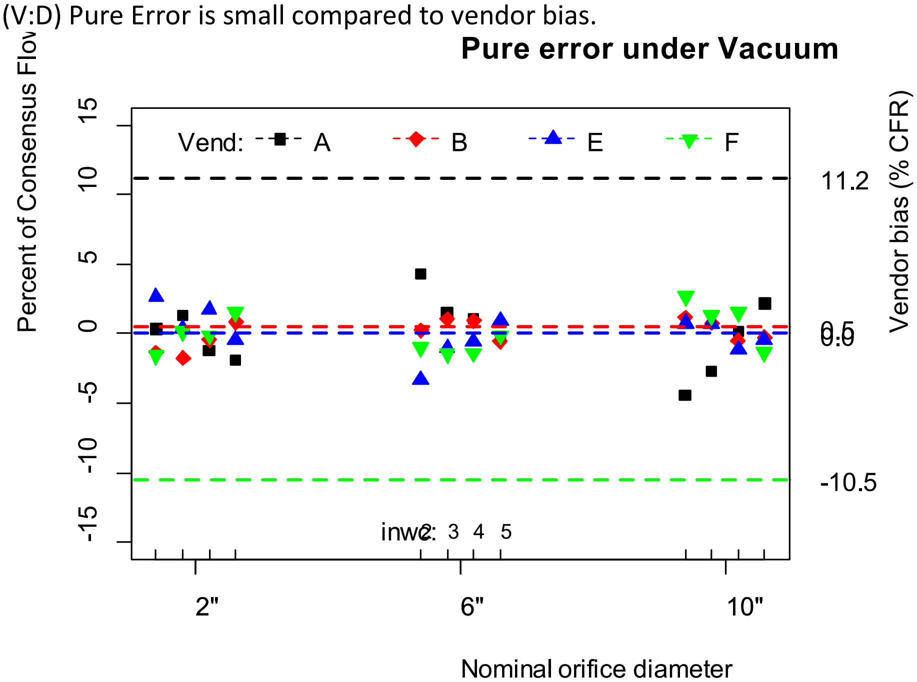

Figure 7. Pure error under Vacuum.

Annex

8 Symbols

v	vendor (testgroup participant)
p	pressure difference between inlet and outlet
d	nominal diameter of orifice
m	test mode (P or V)
f.vpd	flow rate reported by vendor v for orifice d at pressure p
T.pd	theoretical flow rate
F.pd	hypothetical gold-standard flow rate, independent of vendor
CC.pd	gold standard capacity coefficient, CCpd = Fpd/Tpd
cc.vpd	capacity coefficient reported by vendor ccvpd = fvpd/Tpd
CFR.pd	consensus (mean) flow rate of the 4 participating vendors that reported complete data

9 Analysis of Variance

9.1 Model for a given mode (pressure or vacuum)

log(f.vpd) = log(F.pd) + e.vpd

Subtract log(T.pd) from each side to get the model in terms of capacity coefficients,

log(cc.vpd) = log(CC.vpd) + e.vpd ,

which has the has the same error term.

9.2 R linear model (lm) of flow rate.

log(f.vpd) ~ p:d + v + v:p + v:d + v:p:d

The term p:d is the *consensus flow rate*, a proxy for the gold standard, v is *vendor bias*, and v:p:d serves as the error term, e.vpd. Terms v:p and v:d are vendor bias by pressure and diameter, respectively.

10 Formulas and Definitions

symbol		*formula*	*name*
ℓ_{vpd}	$=$	$\ln(\text{fvpd})$	dependent variable
$\bar{\ell}_{\cdot pd}$	$=$	$\frac{1}{4}\sum_{v=1}^{4}\ell_{vpd}$	$\ln(\text{consensus flow rate})$
$\bar{\ell}_{v\cdot d}$	$=$	$\frac{1}{4}\sum_{p=1}^{4}\ell_{vpd}$	vd mean
$\bar{\ell}_{v\cdot\cdot}$	$=$	$\frac{1}{12}\sum_{p=1}^{4}\sum_{d=1}^{3}\ell_{vpd}$	v mean
$\bar{\ell}_{\cdot\cdot d}$	$=$	$\frac{1}{16}\sum_{v=1}^{4}\sum_{p=1}^{4}\ell_{vpd}$	d mean
$\bar{\ell}_{\cdot\cdot\cdot}$	$=$	$\frac{1}{48}\sum_{v=1}^{4}\sum_{p=1}^{4}\sum_{d=1}^{3}\ell_{vpd}$	grand mean
		$\bar{\ell}_{v\cdot\cdot}-\bar{\ell}_{\cdot\cdot\cdot}$	vendor bias
		$\bar{\ell}_{v\cdot d}-\bar{\ell}_{v\cdot\cdot}-\bar{\ell}_{\cdot\cdot d}+\bar{\ell}_{\cdot\cdot\cdot}$	vendor bias by diameter
		$\ell_{vpd}-\bar{\ell}_{\cdot pd}-\bar{\ell}_{v\cdot\cdot}+\bar{\ell}_{\cdot\cdot\cdot}$	noise
		$\ell_{vpd}-\bar{\ell}_{\cdot pd}-\bar{\ell}_{v\cdot d}+\bar{\ell}_{\cdot\cdot d}$	pure error

11 R Program

```
####################################################################################
#  PVtest ANOVA and Noise Analysis
####################################################################################

library(readxl)
library(emmeans)
# library(lme4)
library(here)
# library(tidyr)
library(EMSaov)

###################################################################################
#  Read Pressure & Vacuum data
#
```

```
####################################################################################
Press <- read_excel(paste0(here(),"/FlowData.xlsx"),
                    sheet = "API2000 Pressure", skip = 1)[,1:16]
Vac   <- read_excel(paste0(here(),"/FlowData.xlsx"),
                    sheet = "API2000 Vacuum", skip = 1)[,1:16]
PV <- rbind(Press,Vac)
  PV$diam.nom <- as.character(PV$diam.nom)
  PV$dp.nom <- as.character(PV$dp.nom)

# Complete data: vendors A,B,E,F; pressures 2,3,4,5

PV.c <- PV[which(PV$dp.iwc > 0 & PV$dp.nom>1 & !(PV$vend %in% c("C","D"))),]

##############################################################
#  Analysis of Variance
##############################################################
# Variables
# ---------
#  SCFH.obs : measured flow rate
#  dp.psi   : measured difference between inlet and outlet pressure (psi)
#
#  Factors
#   diam.nom  : nominal diameter of orifice
#   dp.nom    : nominal difference betw. inlet and outle pressure
#   rig       : test rig (5th or 7th edition)
#   vend      : vendor
#   pv        : pressure or vacuum condition
##############################################################
AOV <- function(mode)  {
  data <- as.data.frame(PV.c[which(PV.c == substr(mode,1,1)),])
  data$y <- log(data$SCFH.obs)

  #  Full ANOVA model

  AOV.lm <- lm(log(SCFH.obs) ~ diam.nom*dp.nom + vend + vend:diam.nom +vend:dp.nom,
               data = data)
  EMS.lm <- EMSanova(y ~
diam.nom*dp.nom*vend,data=data,type=c("F","F","R"),approximate=TRUE)

  # Full model anova table
  AOV <- anova(AOV.lm)
  print(AOV)
  write.csv(AOV,file=paste0("AOV_",mode,".csv"))
```

```
  # consensus flow rates

  consensus.EMM <- emmeans(AOV.lm,~ diam.nom*dp.nom)
    consensus <- as.data.frame(print(summary(regrid(consensus.EMM))))
    consensus$diam.nom <- as.numeric(as.character(consensus$diam.nom))
    consensus$dp.nom <- as.numeric(as.character(consensus$dp.nom))
    sort <- order(consensus$diam.nom,consensus$dp.nom)
    consensus <- consensus[sort,]
    colnames(consensus)[3:4] <- c("SCFH","StdErr")

    # Table
    write.csv(consensus,file=paste0("Consensus_",mode,".csv"))

    # Graph
    y=consensus$SCFH/1000
    x=consensus$dp.nom
    d=consensus$diam.nom
    n <- length(d)
    pch = rep(19,n)
      pch[which(d==6)]=15
      pch[which(d==10)]=17
    plot(y~x,log="y",ylim=c(1,100),pch=pch,cex=1.5, xaxt="n",
         xlab="Pressure (inwc)",ylab="FLOW (1000 scfh)",main=paste("Consensus Flow
Rate
                under ",mode))
         axis(side=1,at=c(2,3,4,5))
         legend("bottomright",c(" 2 in"," 6 in","10 in"),pch=c(19,15,17))
         for(diam in c(2,6,10)){
           which <- which(d==diam)
           lines(y[which]~x[which])
         }

  # vendors vs consensus
  vend.EMM <- emmeans(AOV.lm,"vend")
  vend.deviations <-contrast(vend.EMM,
                             list(A = c( .75,-.25,-.25,-.25),
                                  B = c(-.25, .75,-.25,-.25),
                                  E = c(-.25,-.25, .75,-.25),
                                  F = c(-.25,-.25,-.25, .75)))
  vend.vs.con <- as.data.frame(summary(vend.deviations))
  colnames(vend.vs.con)[1] = "vend"

  df <- vend.vs.con$df[1]
  se <- vend.vs.con$SE[1]
```

```
  two.sigma <- qt(.975,df)*se

  vend.vs.con$percent <- 100*(exp(vend.vs.con$estimate)-1)
  vend.vs.con$lower   <- 100*(exp(vend.vs.con$estimate-two.sigma)-1)
  vend.vs.con$upper   <- 100*(exp(vend.vs.con$estimate+two.sigma)-1)
  vend.vs.con <- vend.vs.con[,c("vend","percent","lower","upper")]
  print(vend.vs.con)
  write.csv(vend.vs.con,file=paste0("vendor_vs_consensus_",mode,".csv"))

  # Total noise
  AOV.vend.lm <- lm(log(SCFH.obs) ~ diam.nom*dp.nom + vend,
               data = data)
  total.noise <- (exp(residuals(AOV.vend.lm))-1)*100


  palette <- c("black","red","blue","green")
  shapes <- c(22,23,24,25)

  col <- palette[as.numeric(as.factor(data$vend))]
  pch <- shapes[as.numeric(as.factor(data$vend))]
  # whole part of x is diameter rank (1,2,3); fractional part is pressure (-.15,-
.05,.05,15)
  x <- as.numeric(data$diam.nom)
    x[which(x==2)]  <-1
    x[which(x==6)]  <-2
    x[which(x==10)] <-3
    x <- x + (as.numeric(factor(data$dp.nom))-2.5)/10
  # ordinates of dotted lines
  v.bias <- round(vend.vs.con$percent,1)
  # wide right margin
  par(oma=c(0,0,0,3))
  ylim<- c(5*floor(min(v.bias)/5),5*ceiling(max(v.bias)/5))
    y.min <- min(ylim)
  plot(total.noise ~ x,type="p",col=col,pch=pch,bg=col,
      xaxt="n",ylim = ylim,main=paste0("Total Noise under ", mode),
      xlab="Nominal orifice diameter",
      ylab="Percent of Consensus Flow Rate")
  # nominal inwc tick marks
    axis(side=1,at=c(1,2,3),labels=c('2"','6"','10"'))
      axis(side=1,at=c(.85,.95,1.05,1.15),labels=c(NA,NA,NA,NA),tck=.02)
      axis(side=1,at=c(.85,.95,1.05,1.15)+1,labels=c(NA,NA,NA,NA),tck=.02)
      axis(side=1,at=c(.85,.95,1.05,1.15)+2,labels=c(NA,NA,NA,NA),tck=.02)
    text(y=y.min+1,x=1.70,labels="inwc:")
    text(y=rep(y.min+1,3),x=c(.85,.95,1.05,1.15)+1,labels=c(2,3,4,5),cex=.8)
```

```
    axis(side=4,at=round(vend.vs.con$percent,1),las=2,tck=0)
      mtext("Vendor bias (% CFR)",side=4,line=3)
    legend("top",c("Vend: ","A","B","E","F"),pch=c(NA,shapes),lty=c(NA,2,2,2,2),
           col=c("black",palette),pt.bg=c("black",palette), ncol=5,bty="n",x.intersp
= .5)
    for(v in 1:4) {
      lines(y=rep(vend.vs.con$percent[v],2),x=c(0,6),lty=2,col=palette[v],lwd=2)
    }

  # Vendor by Orifice bias
    # Noise
    AOV.vend.lm <- lm(log(SCFH.obs) ~ diam.nom*dp.nom + vend,
                          data = data)
    AOV.vendXorifice.lm <- lm(log(SCFH.obs) ~ diam.nom*dp.nom + vend + diam.nom:vend,
                          data = data)
    EMM.vend <- as.data.frame(emmeans(AOV.vend.lm, ~ diam.nom*vend))
    EMM.vendXorifice <- as.data.frame(emmeans(AOV.vendXorifice.lm, ~ diam.nom*vend))
    y <- 100*(exp(EMM.vend$emmean-EMM.vendXorifice$emmean)-1)
    x <- as.numeric(EMM.vendXorifice$diam.nom)
    v.bias <- round(vend.vs.con$percent,1)
    col <- palette[EMM.vendXorifice$vend]
    pch <- shapes[EMM.vendXorifice$vend]
    plot(y ~ x,type="p",col=col,pch=pch,bg=col,
         xaxt="n",ylim = ylim,main=paste0("Vendor bias by Orifice size under ",mode),
         xlab="Nominal orifice diameter",
         ylab="Percent of Consensus Flow Rate")
    axis(side=1,at=c(1,2,3),labels=c('2"','6"','10"'))
    axis(side=4,at=round(vend.vs.con$percent,1),las=2,tck=0)
    mtext("Vendor bias (% CFR)",side=4,line=3)
    legend("top",c("Vend: ","A","B","E","F"),pch=c(NA,shapes),lty=c(NA,2,2,2,2),
           col=c("black",palette),pt.bg=c("black",palette), ncol=5,bty="n",x.intersp
= .5)
    for(v in 1:4) {
      lines(y=rep(vend.vs.con$percent[v],2),x=c(0,6),lty=2,col=palette[v],lwd=2)
    }

    # pure error
    AOV.full.lm <- lm(log(SCFH.obs) ~ diam.nom*dp.nom + vend + vend:diam.nom +
vend:dp.nom,
                      data = data)

    pure.error <- 100*(exp(residuals(AOV.full.lm))-1)
```

```
    col <- palette[as.numeric(as.factor(data$vend))]
    pch <- shapes[as.numeric(as.factor(data$vend))]
    x <- x + (as.numeric(factor(data$dp.nom))-2.5)/10
    v.bias <- round(vend.vs.con$percent,1)
    plot(pure.error ~ x,type="p",col=col,pch=pch,bg=col,
         xaxt="n",ylim = ylim,main=paste0("Pure error under ",mode),
         xlab="Nominal orifice diameter",
         ylab="Percent of Consensus Flow Rate")
    axis(side=1,at=c(1,2,3),labels=c('2"','6"','10"'))
    # nominal inwc tick marks
    axis(side=1,at=c(1,2,3),labels=c('2"','6"','10"'))
    axis(side=1,at=c(.85,.95,1.05,1.15),labels=c(NA,NA,NA,NA),tck=.02)
    axis(side=1,at=c(.85,.95,1.05,1.15)+1,labels=c(NA,NA,NA,NA),tck=.02)
    axis(side=1,at=c(.85,.95,1.05,1.15)+2,labels=c(NA,NA,NA,NA),tck=.02)
    text(y=y.min+1,x=1.70,labels="inwc:")
    text(y=rep(y.min+1,3),x=c(.85,.95,1.05,1.15)+1,labels=c(2,3,4,5),cex=.8)

    axis(side=4,at=round(vend.vs.con$percent,1),las=2,tck=0)
    mtext("Vendor bias (% CFR)",side=4,line=3)
    legend("top",c("Vend: ","A","B","E","F"),pch=c(NA,shapes),lty=c(NA,2,2,2,2),
           col=c("black",palette),pt.bg=c("black",palette), ncol=5,bty="n",x.intersp
= .5)
    for(v in 1:4) {
      lines(y=rep(vend.vs.con$percent[v],2),x=c(0,6),lty=2,col=palette[v],lwd=2)
    }
}

AOV("Pressure")
AOV("Vacuum")
```