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Hydraulic fluid power - Determination of derived displacement of positive displacement pumps and motors - Part 1: Two-step Toet-method

CD stage

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Foreword

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This document was prepared by Technical Committee ISO/TC 131, *Fluid power systems*, Subcommittee SC 08, *Product testing*.

A list of all parts in the ISO 8426 series can be found on the ISO website.

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Introduction

In hydraulic fluid power systems, power is transmitted and controlled through a liquid under pressure within an enclosed circuit. Two types of components of such systems are the positive displacement pumps and motors. One of the technical parameters of these components is the derived displacement, also known as derived capacity. This document is intended to describe the test procedure and analytical approach of the Toet-method for determining the derived displacement of hydraulic fluid power positive displacement pumps and motors.

Hydraulic fluid power - Determination of derived displacement of positive displacement pumps and motors - Part 1: Two-step Toet-method

1 Scope

This document specifies the Toet method for the determination of the derived displacement of hydraulic fluid power positive displacement pumps and motors under steady-state conditions. A single value for the derived displacement is determined from measurements at multiple shaft speeds.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 4409:2019, *Hydraulic fluid power — Positive-displacement pumps, motors and integral transmissions — Methods of testing and presenting basic steady state performance*

ISO 5598:2020, *Fluid power systems and components — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 5598:2020, the following apply:

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
unit
pump or motor

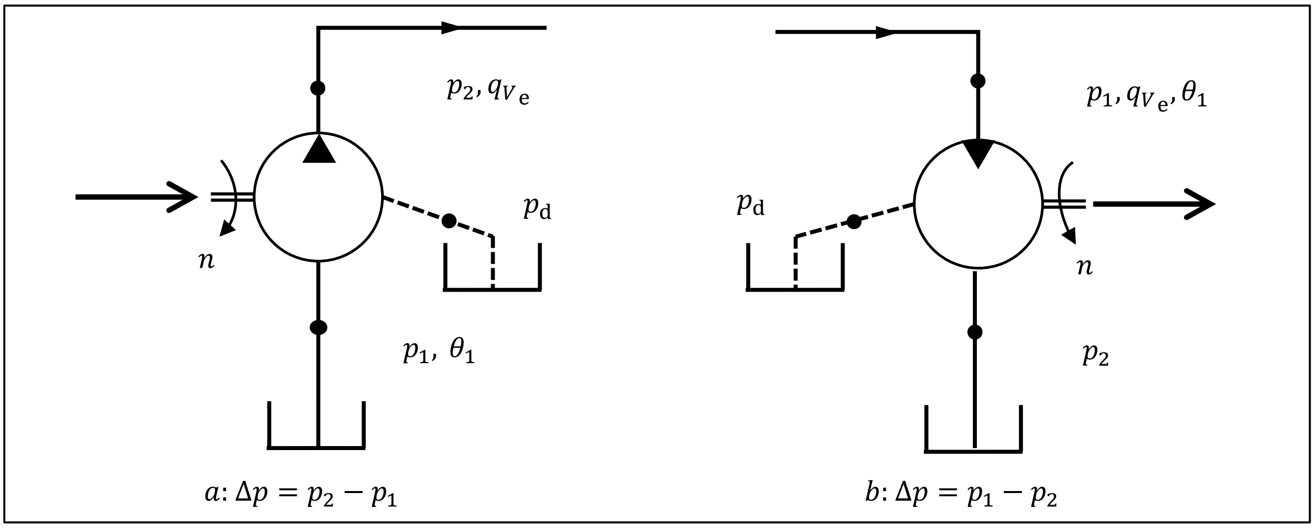
4 Symbols, subscripts, and graphical symbols

The general symbols used throughout this standard are shown in Table 1 based on ISO 4391:1983 (1). Graphical symbols are depicted in accordance with ISO 1219 series (2).

A diagram showing the use of symbols, subscripts, and graphical symbols is shown in Figure 1. Figure 1 depicts the measured location of each symbol and the use of graphical symbols for pumps and motors.

Table 1—Terms, symbols, description, and units.

Symbol	Term	Units
α_i	slope of high pressure flow vs shaft speed	cm³/rev
j	number of shaft speeds	-
k	number of measurement points	-
ℓ	number of differential pressures	-
n	shaft speed	rev/min
Δp	differential pressure	bar
p_1	inlet pressure	bar
p_2	outlet pressure	bar
p_d	case pressure	bar
$q_{V\mathrm{e}}$	high pressure flow	L/min
θ_1	inlet temperature	°C
V_i	derived displacement	cm³/rev



Key

a Pump differential pressure

b Motor differential pressure

Figure 1—Example use of symbols, subscripts, and graphical symbols for pumps and motors.

5 Test Procedure

5.1 Requirements

Measurement accuracy class according to ISO 4409:2019 Clause A.2 shall be used for all measured quantities.

ISO 4409:2019 Clause 5.1 and its subclauses shall be used for test procedure requirements.

5.2 Positive displacement pump test procedure

ISO 4409:2019 Clause 5.2 and its subclauses shall be used for the pump testing procedure.

5.3 Positive displacement motor test procedure

ISO 4409:2019 Clause 5.3 and its subclauses shall be used for the motor testing procedure.

5.4 Number of steady-state shaft speeds and differential pressures

The minimum number shaft speeds shall be four. The minimum number of differential pressures shall be four. The minimum number of measurement points shall be 16 (four shaft speeds times four differential pressures). Five or more shaft speeds and five or more differential pressures should be used. This implies 25 or more measurement points should be used.

The shaft speed should be increased in equal increments from minimum shaft speed to maximum shaft speed of the unit but may be spaced in unequal increments. The differential pressure should be increased in equal increments from minimum differential pressure to maximum differential pressure of the unit but may be spaced in unequal increments.

5.5 Variable displacement unit

The data for performing the estimation of the derived displacement of variable displacement pump or motor shall be obtained following ISO 4409:2019 Subclause 5.2.4 and 5.3.4. Derived displacement of a unit at partial displacement shall be estimated using the procedure presented in Clause 6.

5.6 Unit for reverse flow and reverse rotation

The derived displacement of a unit may depend on the flow direction and on the direction of rotation. If the derived displacement is of interest for both flow directions, respectively for both directions of rotation, the unit shall also be tested at both flow directions, respectively at both directions of rotation.

6 Calculation of derived displacement

6.1 General

The mathematical definition of the derived displacement is shown in Formula 1. Expressing Formula 1 in words, the derived displacement is the slope of the high pressure flow with respect to shaft speed evaluated at zero differential pressure. One of the fundamental implications of the Toet method is derived displacement is assumed to be independent of speed and differential pressure according to (3) Clause 4 and (4) Clause 4. Therefore, the task of finding the derived displacement is to find the slope of the high pressure flow with respect to shaft speed at zero differential pressure.

$$V_i = \left(\frac{\partial q_{V_e}}{\partial n}\right)_{\Delta p=0} \qquad (1)$$

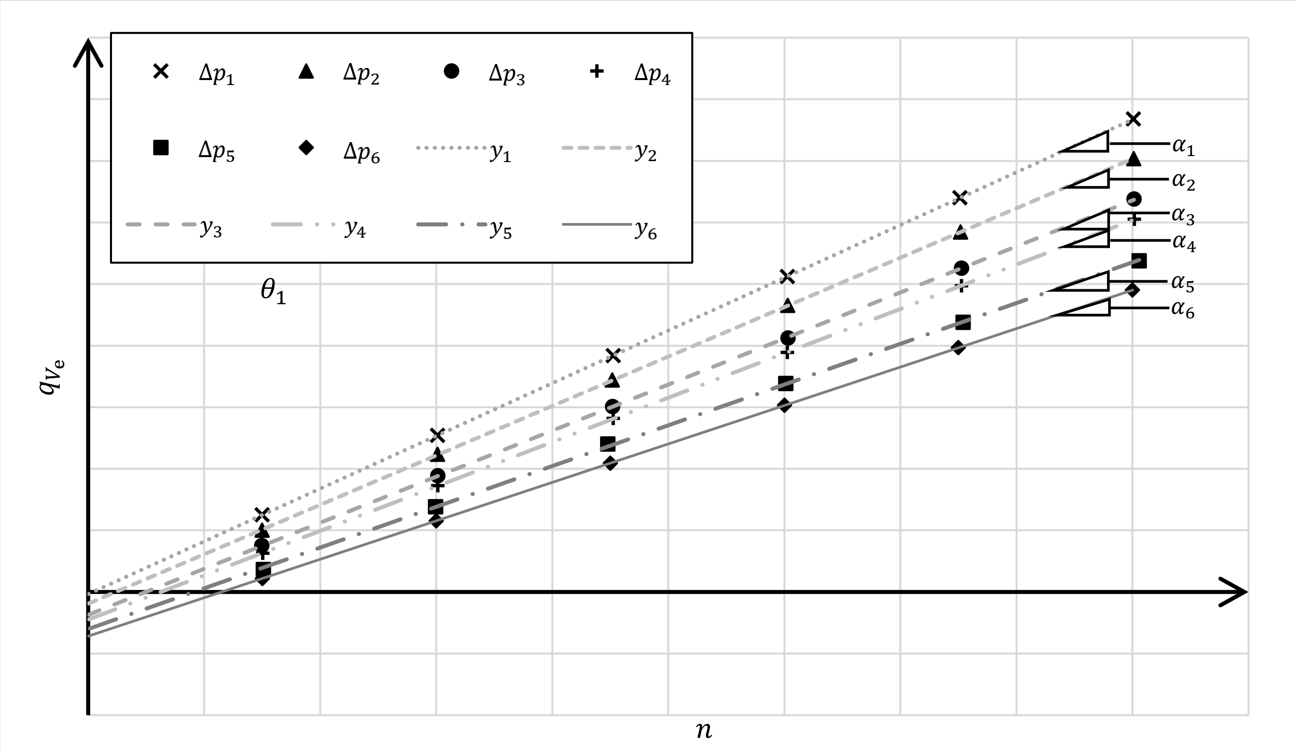
Where

q_{V_e}	is the high pressure flow
n	is the shaft speed
V_i	is the derived displacement
$(\ )_{\Delta p=0}$	implies evaluating the expression at Δp of 0

6.2 The Two-step Toet Method

The steps below shall be used to calculate the derived displacement using the Two-Step Toet Method (see references (3) and (4) for more information):

1. The high pressure flow, q_{V_e}, shall be measured at various shaft speeds, n for a nominal differential pressure, Δp_1; An ordinary least squares regression of a line shall be performed between high pressure flow and shaft speed to find the slope, α_1. The regression should be done automatically using a spreadsheet program or statistical software; the regression may be carried out via the formulas in Annex C. Repeat this step for all the nominal differential pressures.

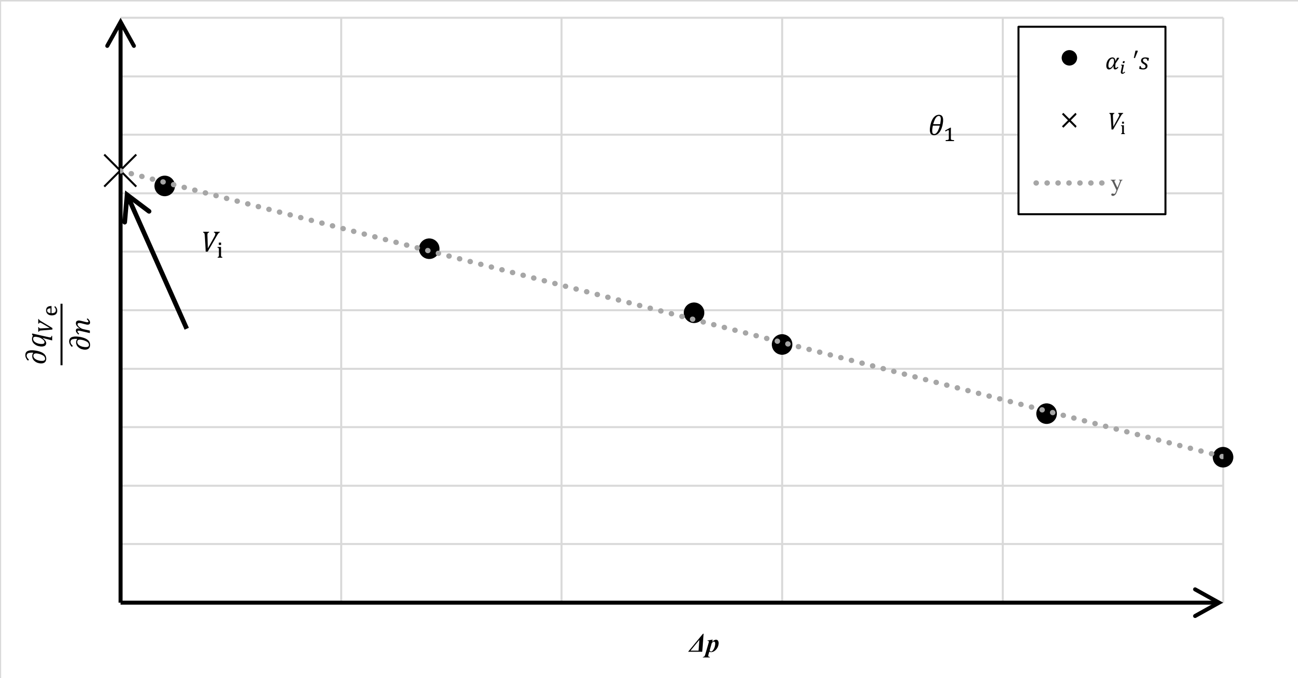


Key

n	shaft speed
q_{V_e}	high pressure flow
α_i	the slope of fitted $\Delta p_i \leq i \leq \ell$.
θ_1	constant inlet temperature
y_i	linear regression $\Delta p_i \leq i \leq \ell \leq i \leq \ell$

Figure 2—The first step of the Two-step Toet Method

2. An ordinary least squares regression of a line shall be used to find the intercept of the slopes α_i with respect to the Δp. The intercept is derived displacement, V_i. This regression should be done automatically using a spreadsheet program or statistical software; the regression may be carried out via the formulas in Annex C. This step is depicted in Figure 3.



Key

Δp	differential pressure
$\frac{\partial q_{V_e}}{\partial n}$	displacement
α_i 's	slopes found in step one
θ_1	constant inlet temperature
V_i	derived displacement
y	linear regression line

Figure 3—The second step of the Two-Step Toet Method

6.2

For more information on guidance related to regression, see Annex B Residual and regression metrics.

7 Test Report

This Clause may be used as a guideline for reporting the results of the test and analysis. For an example pump test report, see A.1. For an example motor test report, see A.2. A minimal test report should be written and should include the following:

General information:

a) Test date and location;
b) Description of the unit under test, including model, serial number, and date of manufacture if available;
c) Shaft speed, n, operating range of the unit;
d) Differential pressure, Δp, operating range of the unit;

e) Displacement range if applicable and value of current fixed displacement (i.e. displacement is locked);
f) Description of the test circuit, including the location of flow-meters (see ISO 4409:2019 Figure 1, Figure 2, and Figure 3) and test circuit filtration details (see ISO 4409:2019 5.1.1);
g) Measurement accuracy class (see ISO 4409:2019 A.1 and A.2);
h) Nominal test fluid properties. This includes, at a minimum, fluid name and the properties of kinematic viscosity and density at the nominal inlet temperature and atmospheric pressure; (see ISO 4409:2019 5.1.3);
i) Nominal inlet fluid test temperature, θ_1 (see ISO 4409:2019 5.1.4);
j) Nominal case pressure, p_{d}, if appropriate (see ISO 4409:2019 5.1.5);
k) The time period and rate for data acquisition rate for flow rate measurements (see ISO 4409:2019 5.1.6);

The derived displacement of a positive displacement pump or motor forms the basis for the determination of the volumetric and mechanical efficiency of the unit under test in accordance with ISO 4409:2019. At a minimum the following measurements shall be presented:

l) Inlet pressure, p_1;
m) Outlet pressure, p_2;
n) Differential pressure, Δp;
o) Shaft speed, n;
p) Inlet temperature, θ_1;
q) High pressure flow, $q_{V_{\mathrm{e}}}$ (see ISO 4409:2019 5.2.1.1, 5.2.1.2, or 5.3.1);

The following derived quantities shall be presented:

r) Derived displacement, V_{i};
s) Values of coefficients and correlation coefficients.

Annex A
(informative)
Test report examples

A.1 Pump test report example

A.1.1 Raw Data

Table A.1 shows the raw data for analysis in the pump test report example.

Table A.1—Raw data for pump example

Nominal Delta Pressure [bar]	Nominal Shaft Speed [rev/min]	Inlet Pressure [bar]	Outlet Pressure [bar]	Shaft Speed [rev/min]	Inlet Temperature [°C]	Delta Pressure [bar]	High Pressure Flow [L/min]
10	300	-0.10	10.01	299.4	49.6	10.1	25.64
10	600	-0.06	10.01	602.2	49.7	10.1	51.65
10	900	0.04	9.99	904.9	49.7	10.0	77.76
10	1200	-0.04	9.99	1205.3	50.3	10.0	103.70
10	1500	0.08	10.01	1502.6	49.7	9.9	129.46
10	1800	-0.03	10.00	1801.7	49.6	10.0	155.31
70	300	-0.02	69.87	299.8	50.1	69.9	24.24
70	600	0.03	70.00	602.2	50.0	70.0	50.43
70	900	0.02	69.92	903.1	49.8	69.9	76.11
70	1200	-0.07	70.47	1205.9	50.0	70.5	102.05
70	1500	-0.07	70.41	1503.8	49.6	70.5	127.37
70	1800	-0.05	70.46	1801.8	50.1	70.5	152.70
130	300	-0.06	130.45	299.2	50.0	130.5	22.88
130	600	0.00	130.05	602.8	49.6	130.1	48.43
130	900	-0.03	130.35	904.0	50.3	130.4	73.84
130	1200	0.07	130.24	1206.0	49.8	130.2	99.00
130	1500	-0.04	129.81	1505.0	49.7	129.9	124.41
130	1800	-0.03	129.87	1802.5	49.7	129.9	149.73
150	300	-0.07	149.99	300.6	50.4	150.1	21.63
150	600	-0.09	150.39	602.8	49.6	150.5	46.94
150	900	0.01	149.84	904.7	49.7	149.8	72.01
150	1200	-0.06	150.43	1205.0	49.8	150.5	96.90
150	1500	-0.01	150.38	1505.1	49.7	150.4	121.79
150	1800	-0.03	150.29	1803.1	50.1	150.3	146.68
210	300	0.05	210.97	301.7	49.6	210.9	20.03
210	600	-0.10	210.91	598.6	49.6	211.0	45.02
210	900	0.04	209.09	895.4	49.9	209.1	69.76
210	1200	-0.05	209.28	1202.4	49.7	209.3	94.24
210	1500	0.00	209.81	1507.9	50.4	209.8	118.81
210	1800	-0.08	209.48	1811.6	49.9	209.6	143.45

A.1.2 Example report

Test time: 2020-03-24 13:03
Test location: City, State or Province, Country
Unit Tested: ACME Series XYZ Fixed Displacement Pump, model 365, serial 1234ABCD
Shaft speed range: [300rev/min, 1800rev/min]
Differential pressure range: [0bar, 210bar]
Description of test circuit:

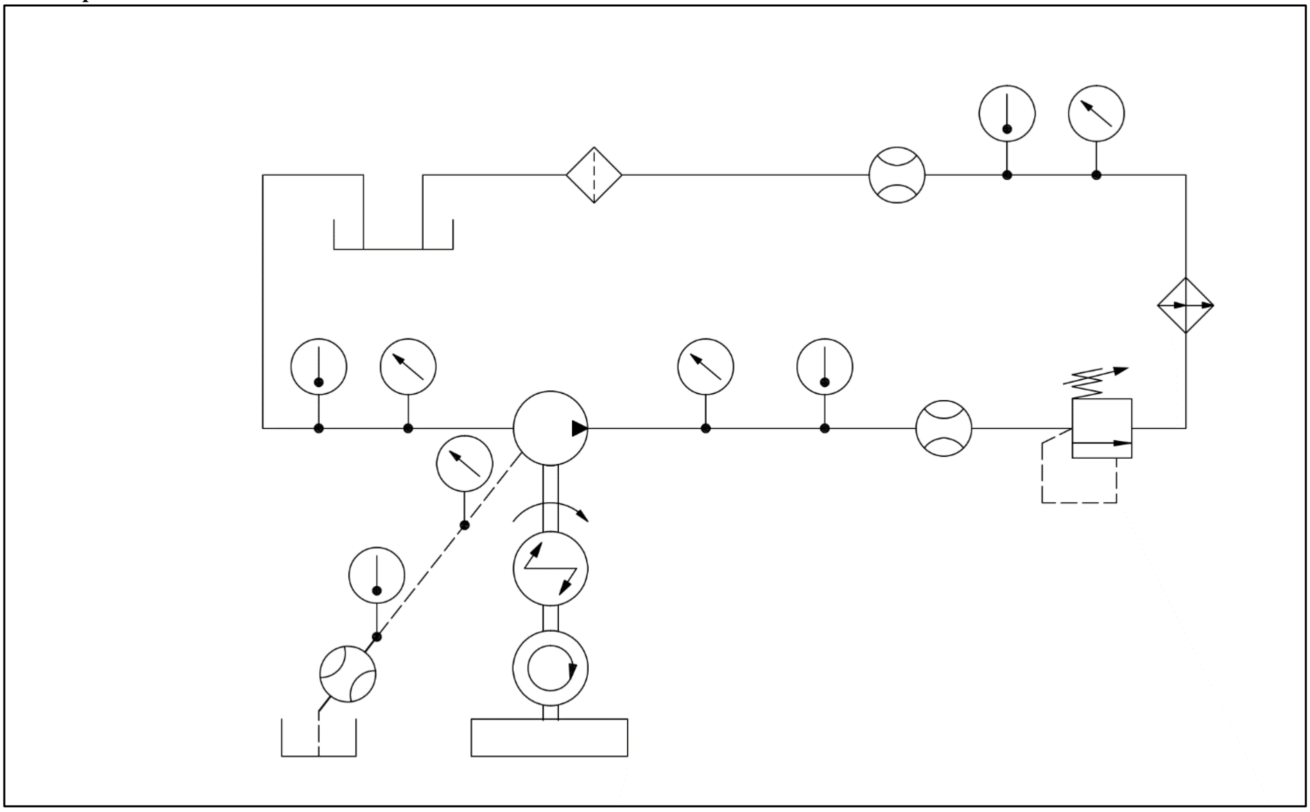
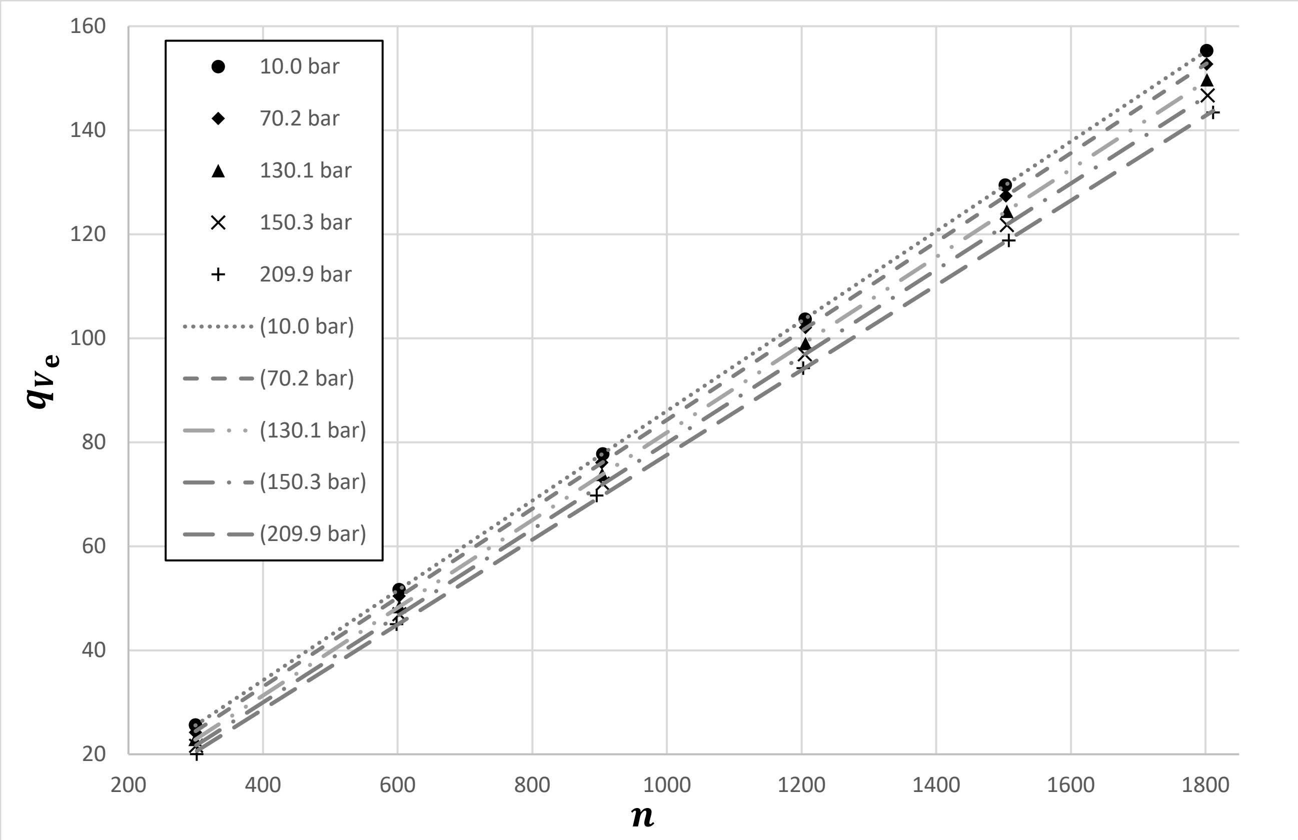


Figure A.1—Example test circuit for an open circuit pump unit
Test circuit filtration details: 23 micron

Measurement Accuracy Class: A
Test fluid: ABCDOil-46
kinematic viscosity of 30cSt at 50°C and atmospheric pressure
density of 860kg/m^3 at 50°C and atmospheric pressure
Nominal inlet temperature: $\theta_1 = 50$°C
Nominal case pressure: $p_{\mathrm{d}} = 1.5$bar
Time interval for flow rate measurement: 10sec and 100Hz

A.1.2.1 Two-step Toet Method Results

Figure A.2 and Figure A.3 show the graphs first and second step respectively. Table A.1 and Table A.2 are the results of the first and second step respectively.



Key

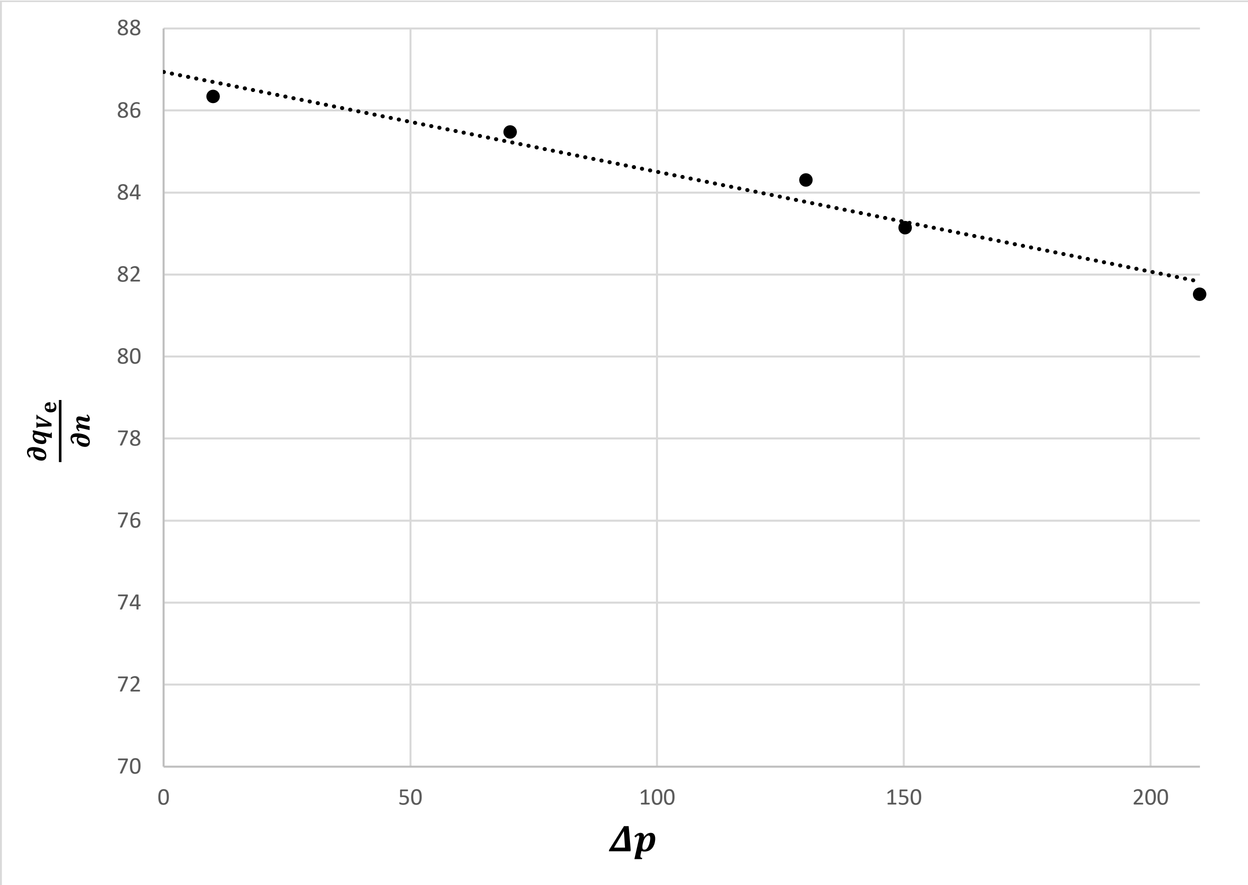
q_{V_e} high pressure flow at the outlet of the pump, L/min.

n shaft speed, rev/min.

Figure A.2—First step of Two-step Toet Method for the pump example

Table A.1—Results for first step of the pump example

Nominal Delta Pressure [bar]	Delta Pressure Average [bar]	Slope of Fitted Line [cm³/rev]	Intercept of Fitted Line [L/min]	Correlation Coefficient R^2
10	10.0	86.341	-5.1390	0.9999981
70	70.2	85.482	-5.5299	0.9999904
130	130.2	84.307	-5.6907	0.9999902
150	150.3	83.148	-5.2557	0.9999974
210	209.9	81.525	-3.9552	0.9998639



Key

$\frac{\partial q_{V_e}}{\partial n}$ displacement

Δp differential pressure

Figure A.3—Second step of Two-step Toet Method for pump example

Table A.2—Results of second step for pump example

Slope [(cm³/rev)/bar]	Intercept, V_i [cm³/rev]	Correlation Coefficient R^2
-0.02433	86.937	0.959491301

A.2 Motor test report example

A.2.1 Raw data

Table A.3 shows the raw data for analysis in the motor test report example.

Table A.3—Raw Data for motor example.

Nominal Differentia l pressure [bar]	Nominal Shaft Speed [rpm]	Outlet Pressure [bar]	Inlet Pressure [bar]	Shaft Speed [rpm]	Inlet Temperature [°C]	Differentia l pressure [bar]	High Pressure Flow [L/min]
30	300	1.98	31.5	300.8	50.5	29.5	31.68
30	600	1.98	31.7	600.8	50.3	29.7	59.32

Nominal Differential pressure [bar]	Nominal Shaft Speed [rpm]	Outlet Pressure [bar]	Inlet Pressure [bar]	Shaft Speed [rpm]	Inlet Temperature [°C]	Differential pressure [bar]	High Pressure Flow [L/min]
30	900	1.97	32.1	901.7	50.3	30.1	86.70
30	1200	1.98	32.2	1200.9	50.3	30.2	113.94
30	1500	1.99	31.6	1498.4	50.3	29.6	141.44
70	300	1.97	71.9	301.7	50.2	69.9	29.66
70	600	1.98	71.9	601.7	50.4	69.9	56.77
70	900	1.97	71.8	902.6	50.2	69.8	83.60
70	1200	1.97	71.6	1201.8	50.3	69.6	110.44
70	1500	1.98	71.7	1498.5	50.4	69.7	137.00
110	300	1.98	112.2	301.7	50.0	110.2	28.05
110	600	1.98	111.6	601.8	49.5	109.6	54.75
110	900	1.99	112.0	903.5	50.2	110.0	81.18
110	1200	1.99	112.3	1201.9	50.4	110.3	107.75
110	1500	1.99	112.2	1500.3	49.5	110.2	134.31
150	300	1.98	151.7	301.8	49.8	149.7	26.16
150	600	1.98	151.6	602.7	50.0	149.6	52.73
150	900	1.98	152.2	903.6	49.6	150.2	79.16
150	1200	1.97	151.7	1203.7	49.6	149.7	105.46
150	1500	1.99	152.0	1499.5	49.9	150.0	131.48
190	300	1.99	190.3	298.5	49.9	188.3	24.46
190	600	2.07	192.0	599.7	49.5	189.9	50.71
190	900	2.09	191.4	908.7	50.4	189.3	76.83
190	1200	1.92	192.8	1194.7	49.6	190.9	102.99
190	1500	1.95	191.6	1514.2	50.1	189.7	128.58

A.2.2 Example report

Test time: 2020-03-25 11:05
Test location: City, State or Province, Country
Unit Tested: ACME Series XYZ Variable Displacement Motor, model 123, serial ABCD1234
Shaft speed range: [300rev/min, 1500rev/min]
Differential pressure range: [0bar, 190bar]
Displacement Range: [0cm^3/rev, 92cm^3/rev]. Fixed at 92cm^3/rev
Description of test circuit:

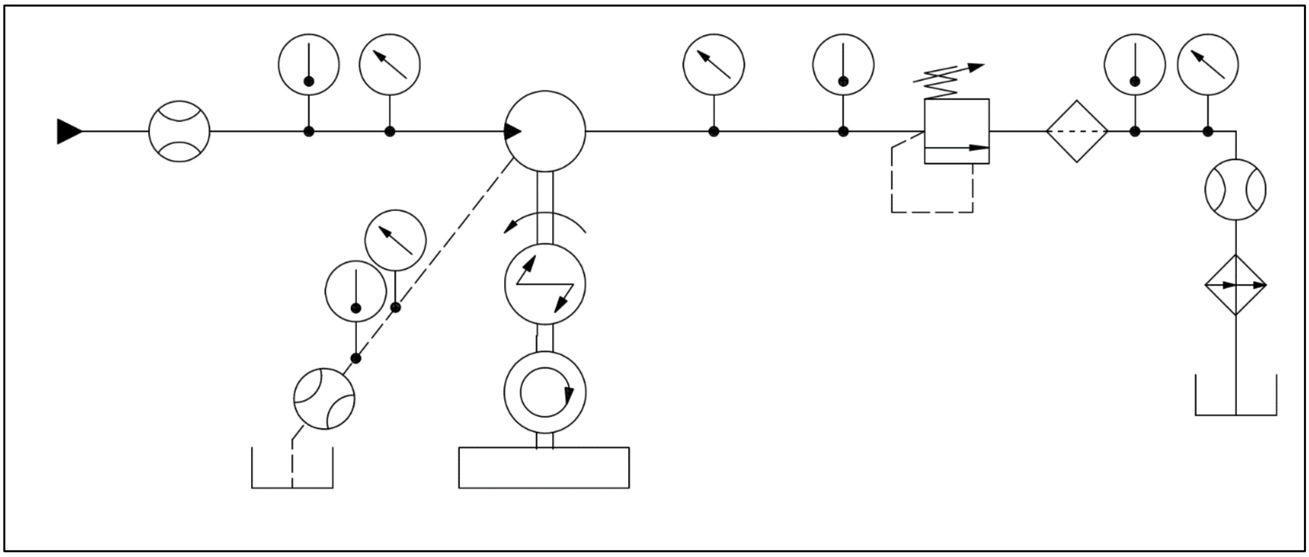
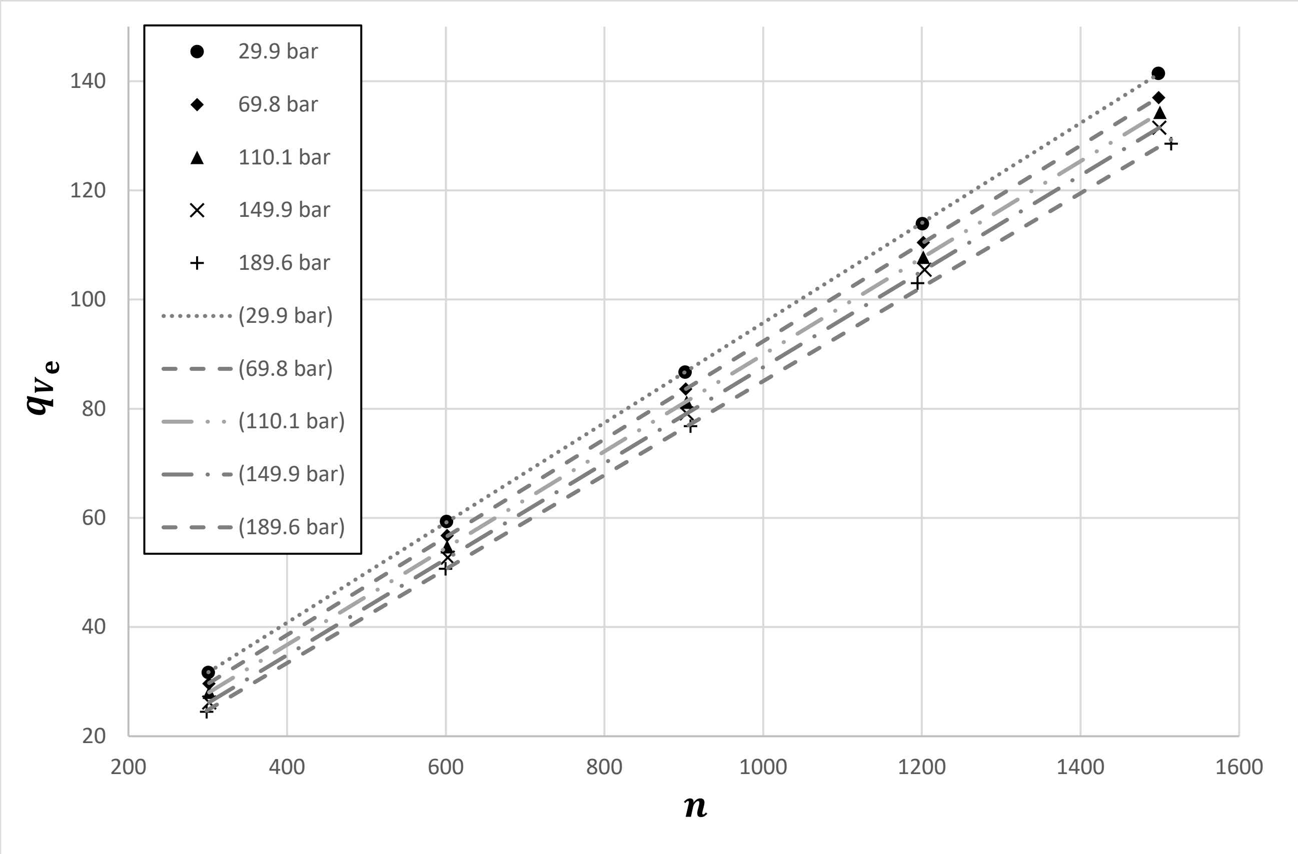


Figure A.4—Example test circuit for motor unit
Test circuit filtration details: 23 micron

Measurement Accuracy Class: A
Test fluid: ABCDOil-46
kinematic viscosity of 30cSt at 50°C and atmospheric pressure
density of 860kg/m^3 at 50°C and atmospheric pressure
Nominal inlet temperature: $\theta_1 = 50$°C
Nominal case pressure: $p_\mathrm{d} = 1.25$bar
Time interval for flow rate measurement: 10sec and 100Hz

A.2.2.1 Two-step Toet Method Results

Figure A.5 and Figure A.6 show the graphs for the first and second steps respectively. Table A.4 and Table A.5 are the results of the first and second step respectively.



Key

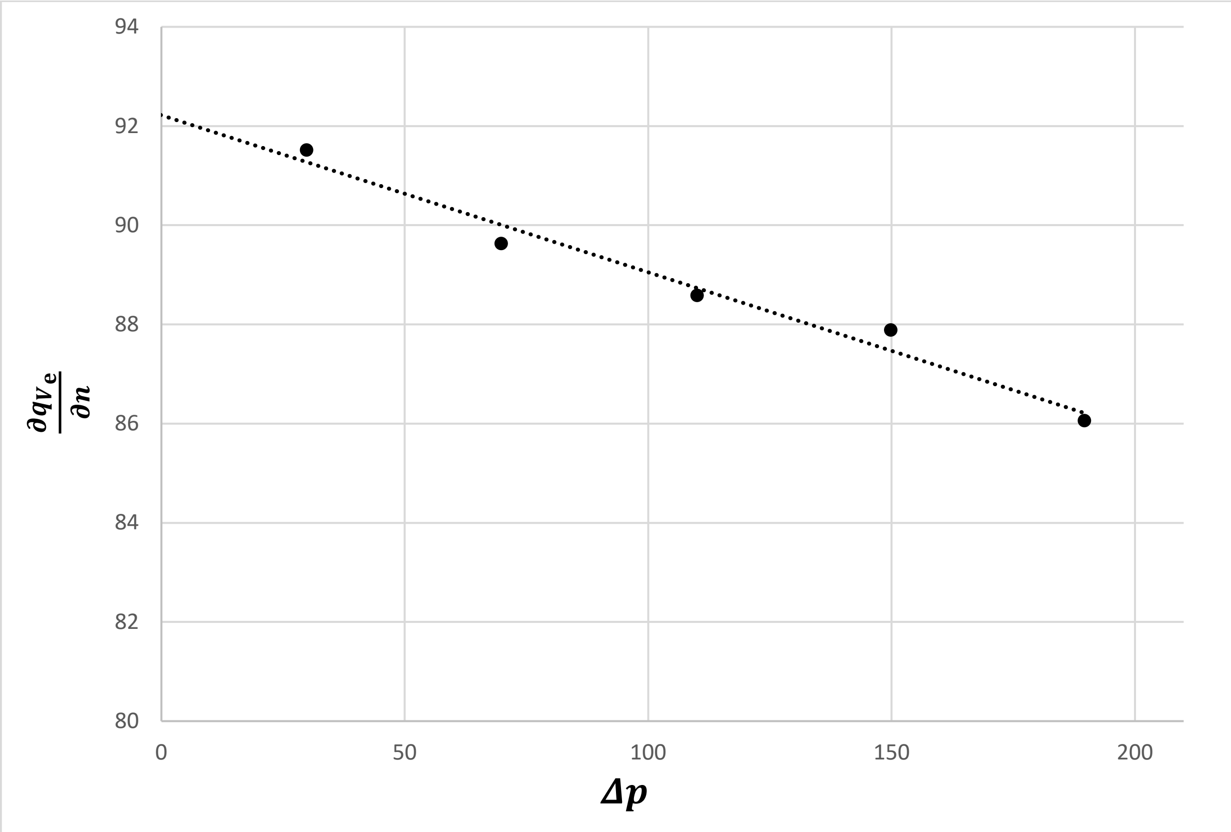
$q_{V\,e}$ high pressure flow at the outlet of the pump, L/min.

n shaft speed, rev/min.

Figure A.5—First step of Two-step Toet Method for motor example

Table A.4—Results for first step for the motor example

Nominal Differential pressure [bar]	Differential pressure Average [bar]	Slope of Fitted Line [cm³/rev]	Intercept of Fitted Line [L/min]	Correlation Coefficient R^2
30	29.9	91.523	-1.4390	0.99999200
70	69.8	89.638	-2.3146	0.9999964
110	110.1	88.586	-2.8567	0.9999923
150	149.9	87.896	-2.6920	0.9999985
190	189.6	86.061	-1.0130	0.9989963



Key

$\frac{\partial q_{V_e}}{\partial n}$ displacement

Δp differential pressure

Figure A.6—Second step of Two-step Toet Method for motor example

Table A.5— Results of second step for motor example

Slope [(cm³/rev)/bar]	Intercept, V_i [cm³/rev]	Correlation Coefficient R^2
-0.03171	92.222	0.974343114

Annex B
(informative)
Residual and regression metrics

B.1 Residual and regression metrics

Evaluation of the residuals from regression analysis is helpful for creating useful models and assessing the validity of derived displacement:

a) The root mean square error (RMSE)—also referred to as standard error—is a measure of the standard deviation of the residuals of the regression. The smaller the value, the better the model fits the data. The RMSE is a metric regularly available as an output of a spreadsheet program or statistical software. The equation for RMSE is shown in Formula B.1 to clarify its definition.

$$S = \sqrt{\frac{\sum_{i=1}^{m}(y_i - \hat{y}_i)^2}{m - r - 1}} \quad \textbf{B.1}$$

where
S is Root Mean Square Error (RMSE)
m is the number of samples
r is the number of fitted linear terms not including the constant. For the One-Step Toet Method, r is three.
y_i is ith measured value
$\hat{y}_i$ is ith fitted response

b) The correlation coefficient (R^2) is a metric for assessing how well a model fits the data. It measures the proportion of variation in the data for which the model accounts. An $R^2$of 0.95 is expected for derived displacement with values approaching or slightly exceeding 0.99 observed in some cases.

Regular or cyclic patterns in the residuals indicates that the residuals contain unmodeled systematic errors. Analyze the residuals for patterns to identify problems with the test and regression.

Annex C
(informative)
Formulas for fitting a line

The regression equation for a line is shown in Formula C.1. The intercept, a, and the slope, b, are found via Formula C.2 and Formula C.3 respectively. Formula C.2 and Formula C.3 are based on ordinary least squares regression for fitting a line.

$$y = a + bx$$ where x is the independent variable y is the dependent variable a is the intercept b is the slope	**C.1**

$$a = \frac{(\sum y)(\sum x^2) - (\sum x)(\sum xy)}{m(\sum x^2) - (\sum x)^2}$$ where x is the measured independent variable y is the measured dependent variable a is the intercept m is the number of points	**C.2**

$$b = \frac{m(\sum xy) - (\sum x)(\sum y)}{m(\sum x^2) - (\sum x)^2}$$ where x is the measured independent variable y is the measured dependent variable b is the slope m is the number of points	**C.3**

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