



BSI Standards Publication

Pumps — Methods of qualification and verification of the Energy Efficiency Index for rotodynamic pump units

Part 2: Testing and calculation of Energy Efficiency Index (EEI) of single pump units

National foreword

This British Standard is the UK implementation of EN 17038-2:2019, incorporating corrigenda July 2020 and October 2021.

The start and finish of text introduced or altered by corrigendum is indicated in the text by tags. Text altered by CEN corrigenda July 2020 and October 2021 is indicated in the text by AC AC.

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English Version

**Pumps - Methods of qualification and verification of the
Energy Efficiency Index for rotodynamic pump units - Part
2: Testing and calculation of Energy Efficiency Index (EEI)
of single pump units**

Pompes - Méthodes de qualification et de vérification
de l'indice de rendement énergétique des groupes
motopompes rotodynamiques - Partie 2 : Essais et
calcul de l'indice de rendement énergétique (EEI) des
groupes motopompes simples

Pumpen - Methoden zur Qualifikation und Verifikation
des Energieeffizienzindex für Kreiselpumpen - Teil 2:
Prüfung und Berechnung des Energieeffizienzindex
(EEI) einzelner Pumpenaggregate

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European foreword

This document (EN 17038-2:2019+AC:2021) has been prepared by Technical Committee CEN/TC 197 “Pumps”, the secretariat of which is held by AFNOR.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by November 2019, and conflicting national standards shall be withdrawn at the latest by November 2019.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN shall not be held responsible for identifying any or all such patent rights.

This document includes the Corrigendum EN 17038-2:2019/AC:2020 which corrects the heading of 5.2.3 and two formula references in 6.3.4, 1) and 6.3.5, 5) and the Corrigendum EN 17038-2:2019/AC:2021 which corrects Formula (3) in 5.2.3, Formula (13) in 6.2, Formula (33) in 6.4.2, Formulae (B.8) and (B.9) in B.2.1, Formulae (D.3) and (D.4) in D.2 and Formula (D.5) in D.3.2. Corrigendum EN 17038-2:2019/AC:2020 was superseded by and merged into Corrigendum EN 17038-2:2019/AC:2021.

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Introduction

This part of the European Standard is the second part of a series of standards describing a methodology to evaluate energy efficiency performance of single pump units, comprising the pump, the motor with or without frequency converter, based on a non-dimensional numerical value called Energy Efficiency Index (*EEI*). An *EEI* allows the comparison of different pump sizes and types with one common indicator. Physical influences such as pump size, specific speed, pump unit part-load operation, motor-efficiency characteristic and frequency converter influence are implemented into this metric.

Specific requirements for testing and a calculation method for an *EEI*, the so called semi-analytical model of a complete single pump unit, specific flow-time profiles and reference control curves are given in this part of the standard.

EEI is an index to rate pump units according to their energy efficiency but does not replace the need to do a life-time cost analysis regarding energy consumption over the life time of the pump unit.

1 Scope

This document specifies methods and procedures for testing, calculating and determining the Energy Efficiency Index (*EEL*) of rotodynamic glanded single pump units for pumping clean water, including where integrated in other products.

The pump types and sizes covered by this document are described in the normative Annex A.

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.

EN 16480, *Pumps — Minimum required efficiency of rotodynamic water pumps*

EN 17038-1:2019, *Pumps — Methods of qualification and verification of the Energy Efficiency Index for Rotodynamic pumps units — Part 1: General requirements and procedures for testing and calculation of energy efficiency index (EEL)*

EN 60034-1, *Rotating electrical machines — Part 1: Rating and performance (IEC 60034-1)*

EN 60034-2-1, *Rotating electrical machines — Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles) (IEC 60034-2-1)*

EN 60034-2-2, *Rotating electrical machines — Part 2-2: Specific methods for determining separate losses of large machines from tests — Supplement to IEC 60034-2-1 (IEC 60034-2-2)*

EN 60034-30-1, *Rotating electrical machines — Part 30-1: Efficiency classes of line operated AC motors (IE code) (IEC 60034-30-1)*

EN 60038, *CENELEC standard voltages (IEC 60038)*

EN 61800-9-2, *Adjustable speed electrical power drive systems — Part 9-2: Ecodesign for power drive systems, motor starters, power electronics & their driven applications — Energy efficiency indicators for power drive systems and motor starters (IEC 61800-9-2)*

EN ISO 9906:2012, *Rotodynamic pumps — Hydraulic performance acceptance tests — Grades 1, 2 and 3 (ISO 9906:2012)*

EN ISO 17769-1, *Liquid pumps and installation — General terms, definitions, quantities, letter symbols and units — Part 1: Liquid pumps (ISO 17769-1)*

IEC/TS 60034-2-3, *Rotating electrical machines — Part 2-3: Specific test methods for determining losses and efficiency of converter-fed AC induction motors*

3 Terms and definitions

For the purpose of this document, the terms and definitions given in EN ISO 17769-1 and the terms, definitions, symbols and subscripts given in EN 17038-1, together with the following apply.

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

- IEC Electropedia: available at <https://www.electropedia.org/>
- ISO Online browsing platform: available at <https://www.iso.org/obp>

3.1**unit efficiency**

hydraulic power output divided by electric power input also called “wire to water efficiency”

$$\eta_{unit} = \frac{P_{hyd}}{P_1}$$

3.2**constant flow operation**

slight variations of the flow rate around the nominal value

Note 1 to entry: Caused by secondary influences from the process as, for example, due to the (moderately) varying level of liquid in reservoirs, etc. The variation of flow rate occurs typically within the range which is covered by the definition and determination of the Minimum Efficiency Index (*MEI*) of the pump, see EN 16480, and which is from $0,75 \cdot Q_{100} \%$ to $1,1 \cdot Q_{100} \%$.

3.3**variable flow**

widely varying flow rate

Note 1 to entry: Typically, at considerable fractions of the total operating time, the actual demand for pump flow rate Q and pump head H is much lower than the values at the operating point of maximum flow rate which is demanded by the application.

3.4**hydraulic power**

conventional expression of the arithmetic product of the flow Q and the head H and a constant (g is the gravitational constant of $9,81 \text{ m/s}^2$)

3.5**maximum hydraulic power**

absolute maximum $P_{hyd,max}$ of hydraulic power of a pump unit set of parameters which cause the pump unit to generate the curve of maximum hydraulic power

Note 1 to entry: The pump unit needs to be capable and designed to run in maximum operation continuously.

3.6**pump unit best efficiency point, ($Q_{BEP,unit} / H_{BEP,unit}$)**

Flow-Head-Point where the pump unit runs at its best unit efficiency point and at maximum operation

3.7**reference flow rate, $Q_{100\%}$**

flow per time unit [m^3/h] at the Best Efficiency Point (BEP) of the unit

3.8**reference head, $H_{100\%}$**

total differential head [m] at the Best Efficiency Point (BEP) of the unit

3.9**flow-time profile**

pattern of percentiles of time where the pump unit runs at a given flow rate

3.10

Complete Drive Module

CDM

electronic power converter connected between the electric supply and a motor as well as extensions such as protection devices, transformers and auxiliaries (according to EN 61800-2)

3.11

Power Drive System

PDS

combination of CDM and motor

3.12

trimmed impeller

impeller of a pump where the initial full diameter D_{full} reduced to a new diameter D_{trim}

3.13

average impeller diameter

mathematical average of varying outer vane diameter for a single stage pump

3.14

average multistage impeller diameter

mathematical average of all (averaged) impeller diameters of all stages

4 Reference flow-time profiles and reference pressure control curves

4.1 General

When putting single pump units into service an appropriate EEI value shall be made available. The EEI shall be for variable flow (EEI_V) and/or constant flow (EEI_C) according to the demand of the application in which the pump unit is put into service or for which the pump unit is specified when placed on the market. For the determination of the EEI_V or EEI_C the respective reference flow-time profiles and the reference pressure control curves given in Table 1 have to be applied.

Table 1 — Reference flow-time profiles and reference pressure control curves for single pump units

Mode			Reference flow-time profile	Reference pressure control curve	Applicable Q/H test points	EEI applicable
#	Demand of application	Type of Pump Unit				
M1	constant flow	fixed speed	constant flow (Table 2)	Q/H curve of the pump unit	On Q/H curve of the pump unit	EEI_C
M2	variable flow	fixed speed	variable flow (Table 3)	Formula (1)	On Q/H curve of the pump unit	EEI_V
M3	constant flow	variable speed	constant flow (Table 2)	Q/H curve of the pump unit	On Q/H curve of the pump unit (measured at fixed speed)	EEI_C
M4	variable flow	variable speed	variable flow (Table 3)	Formula (1)	Q/H points on curve defined by Formula (1)	EEI_V
M5	constant flow, varying head	variable speed	variable flow (Table 3)	Formula (1)	Q/H points on curve defined by Formula (1)	EEI_V

In case of a bare shaft pump alone to be placed on the market the EEI shall be determined with a reference motor (refer to Class “IE3” in EN 60034-30-1) in mode M1 depending on the nominal speed of the bare shaft pump (either 2-pole type for the pump nominal speed $n_{N,PU} = 2\,900\text{ min}^{-1}$ or is of the 4-pole type for the pump nominal speed $n_{N,PU} = 1\,450\text{ min}^{-1}$). The reference motor shall have a nominal power output which exactly equals the shaft power of the pump at its nominal operating conditions.

4.2 Reference flow-time profiles

The reference flow time profile for constant flow operation is shown in Table 2.

Table 2 — Reference flow-time profile for constant flow operation

Flow Q in % of $Q_{100\%}$	75	100	110
Time Δt in % of total operating time	25	50	25

The reference flow time profile for variable flow operation is shown in Table 3.

Table 3 — Reference flow-time profile for variable flow operation

Flow Q in % of $Q_{100\%}$	25	50	75	100
Time Δt in % of total operating time	44	35	15	6

4.3 Reference pressure control curves

In the case of the variable flow demand, the reference control curve is defined by Formula (1):

$$\frac{H_i}{H_{100\%}} = \left[0,5 + 0,5 \cdot \left(\frac{Q_i}{Q_{100\%}} \right) \right] \quad (1)$$

The values $H_i/H_{100\%}$ at the corresponding values of $Q_i/Q_{100\%}$ of the reference flow-time profile are given according to Formula (1).

The reference pressure control curve defined by Formula (1) with the corresponding hydraulic load points given in Table 2 and 3 in numerical form additionally are plotted graphically in Clause 5, Figure 2.

In the case of the constant flow mode, the reference control curve is the Q/H curve of the actual pump unit applied to define $Q_{100\%}$, $H_{100\%}$ (see also Clause 5, Figure 1).

In the case of the constant flow and varying head demand (mode M5), the reference control curve is defined by Formula (1).

5 Determination of average electric power input $P_{1,avg}$ by test

5.1 General

5.1.1 Test requirements

This clause specifies performance tests and evaluations for pump units which are carried out

- either by a company which places the pump units on the market and/or puts them into service,
- or by an independent institution in the frame of the verification procedure described in EN 17038-1:2019, Clause 6.

Such tests shall provide the necessary information on the actual performance values of test pump units needed for the calculation of the EEI -value according to its definition given in EN 17038-1:2019, Clause 4.

All provisions for the test concerning the pump shall be in accordance with EN ISO 9906, class 2. The exception for input power of 10 kW and below (as allowed for the application of EN ISO 9906 on acceptance tests) shall not be valid.

All provisions for the test concerning an electric motor if it is part of the pump unit and is fed directly from an electric grid shall be in accordance with EN 60034-2-1.

All provisions for the test concerning a Power Drive System (PDS) if part of the pump unit shall be in accordance with EN 61800-9-2.

5.1.2 Test conditions

Tests shall be carried out with clean cold water. The performance of a pump varies substantially with the nature of the liquid being pumped. It is not possible to give general rules whereby performance results measured with clean cold water can be converted to predict performance with water having other properties (temperature, content of solids or gas) or other liquids.

The duration of the test shall be sufficient to obtain repeatable results; especially run-in and warming-up effects of the electric and electronic components of the unit shall be considered.

NOTE 1 Run-in effects may take up to one day operating time.

All measurements shall be made under steady-state conditions (see EN ISO 9906, EN 60034-2-1, EN 60034-2-2 and IEC TS 60034-2-3 and EN 61800-9-2).

NOTE 2 EN 61800-9-2 allows warming up the PDS for measuring the nominal point. All other points can be measured quickly after measuring maximum load without waiting for the steady-state.

The tests should be conducted under conditions where cavitation does not affect the performance of the pump.

NOTE 3 If cavitation exists to a remarkable extent in the test pump during the test, not only the pump head but also the pump efficiency and the power input can deteriorate which leads to an underestimation of the energy efficiency of the pump unit.

For Case 1 in 5.2.1 (motor fed by an electric supply with constant frequency) the electric power supply of the test installation shall fulfil the requirements as specified in EN 60034-1. This requires that

- the voltage shall be in accordance with 7.2 of EN 60038 and EN 60034-1,
- the frequency shall be within $\pm 0,3 \%$ of the rated frequency during measurements.

For Case 2 in 5.2.1 (PDS, i.e. motor combined with and fed by a CDM) the following requirements shall be fulfilled in accordance with EN 61800-9-2:

- When testing a PDS under the load of the pump, slow fluctuations in the measured quantities may be unavoidable. Therefore, for each load point several measurements over a period of time (at least several slip cycles, typically 1 min to 3 min) shall be sampled and the average of these values shall be used for the evaluation.
- Pump units equipped with a PDS shall be measured with a screened cable between CDM and motor of a maximum length of 10 m.
- The measurements shall be done when the PDS is thermally stable (the temperature gradient shall be maximal 2 K per hour).

5.1.3 Measuring instrumentation

For the test procedures described in 5.1.1 measuring instrumentation is needed for the determination of:

- the flow rate Q ;
- the pump head H ;
- the electric power input P_1 .

Since instrument accuracy is generally expressed as a percentage of full scale, the range of the instruments chosen shall be as small as practical.

For analogue instruments the observed values should be in the upper third of the instrument range.

The measuring equipment needed to determine the flow rate Q and the pump head H shall be selected in accordance with EN ISO 9906. Detailed information is given in EN ISO 9906:2012, A.1.

For the determination of the electric power input P_1 in case 1 in 5.2.1 (motor directly fed by the electric grid) the electric input power P_1 is determined based on input voltages U and input currents. All requirements concerning the instrumentation for the measurements of P_1 shall be fulfilled according to EN 60034-2-1.

For the determination of the electric power input P_1 in case 2 in 5.2.1 (motor combined with and fed by a CDM), the electric input power P_1 shall be measured according to “input-output measurement method” in EN 61800-9-2. All requirements concerning the instrumentation for the measurement of P_1 shall be fulfilled according to EN 61800-9-2.

5.2 Calculation of load points

5.2.1 General

As explained in EN 17038-1:2019, Clause 4, the value of the Energy Efficiency Index (*EEL*-value) is based on the electric power input P_1 of the pump unit when the pump is operated at the hydraulic load points specified in EN 17038-1:2019, 4.2. The test aims at determining the electric power input P_1 of the pump unit at the N values of pump flow rate Q defined by the reference flow-time profile.

For the test procedure, different cases shall be distinguished:

- 1) Case 1 Fixed speed operation: the electric motor of the pump unit is fed by a constant stator frequency, either grid frequency or a different frequency fed from a CDM and therefore, can only be operated at (nearly) constant rotational speed n . In this case, only the pump flow rate Q can be controlled during the test. The flow rate Q shall be adjusted to the various values of the reference flow-time profile while the head H generated by the pump is given by the Q - H -curve of the pump at constant motor stator frequency. Besides the electric power input P_1 , the actual values of the pump flow rate Q and head H shall be measured and documented.
- 2) Case 2 Variable speed operation: the pump unit shall be operated at variable rotational speed along a pressure control curve. In the test, the flow rate Q shall be adjusted to the various values of the reference flow-time profile. The pump head H shall be adjusted to the values according to the reference pressure control curve.

For each load point, the flow rate Q which is adjusted and measured shall not deviate from the values according to the reference flow-time profile by more than $\pm 3 \%$ (or $\pm 0,1 \text{ m}^3/\text{h}$, whichever is the largest absolute value).

The measured value H_{meas} shall not deviate more than $\pm 5 \%$ (or $\pm 0,2 \text{ m Head}$, whichever is the largest absolute value) from the values H_i according to the reference pressure control curve.

For pump units where the pump is of the multistage type and which are offered and sold with different numbers of stages, the tests on test pump units which should be representative (in respect to the Energy Efficiency Index) for the type series shall be carried out on pump versions with the actual number of stages for vertical and horizontal multistage pumps.

Measurement shall be done on actual pump impeller diameter.

5.2.2 Determination of $Q_{100 \%}$ and $H_{100 \%}$

As a first step of the test procedure $Q_{100 \%}$ shall be determined. For this purpose, the pump unit shall be set to maximum operation.

Maximum operation for a pump unit running at fixed speed is achieved by feeding the motor with a constant stator frequency, this may be the grid frequency or a different frequency fed from a CDM to run the pump unit at maximum hydraulic power.

Maximum operation for a pump unit running with variable speed is achieved by allowing the controller to adjust the speed of the actual pump unit to values, which derive a curve with maximum hydraulic power.

NOTE In case where the H - Q -curve of the pump is cut off to avoid overload of the motor the $Q_{100\%}$ point could be located at the maximum flow ($Q_{\max}$) of the pump unit (right end of curve) then $Q_{100\%} = Q_{\max}$.

The best efficiency point ($Q_{100\%}/H_{100\%}$) is then located on this pump unit curve.

The point ($Q_{100\%}/H_{100\%}$) defines the flow rate corresponding to the reference flow time profiles and the reference pressure control curve.

Target values of the flow rate Q shall be determined. In the case of variable flow, $H_{100\%}$ is also required so that the head points along the reference pressure control curve can be found. In case of fixed flow, the head values are determined by the pump unit head-flow-curve.

For the purpose of determining the needed H - Q -points of the reference flow time profile and the reference pressure control curve, values of flow rate Q , pump head H and electric power input P_1 shall be measured at maximum operation for a sufficient number of operating points around the expected value of $Q_{\text{BEP,unit}}$.

For the choice of these operating points, the value of $Q_{\text{BEP,PU}}$ at $n = n_{\text{N,PU}}$ given in the documentation of the pump manufacturer can be taken as a preliminary estimation for the expected value of $Q_{100\%}$. It is important to take measurement data in a sufficiently large range of Q below and above the expected value of $Q_{100\%}$ (Recommended $0,7 \cdot Q_{100\%} < Q < 1,3 \cdot Q_{100\%}$).

If the value of $Q_{100\%}$ calculated based on the test points shows that less than 3 of the test points were at values of Q greater than this calculated value, additional test points shall be added to generate at least 3 test points at values of Q greater than $Q_{100\%}$.

The value of $H_{100\%}$ can be calculated by inserting $Q = Q_{100\%}$ into Formula (7).

5.2.3 Determination of part load and over load points and reference control curve

The reference flow points of the flow rate Q_i shall be calculated by the following Formula (2):

$$Q_i = \left(\frac{Q}{100} \right)_i \cdot Q_{100\%} \quad (2)$$

Where the values Q corresponding to the N load points of the reference load flow profile are taken from Table 2 or Table 3.

To determine the $Q_{110\%}$ -point for the case where the H - Q -curve of the pump is cut off to avoid overload of the motor and the $Q_{100\%}$ point could be located at the maximum flow ($Q_{\max}$) of the pump unit (right end of curve) the motor may be overloaded for a short time in the test and the ($Q_{110\%}$, $H_{110\%}$) may be measured or the Formulae (7) and (8) may be used.

In the case of variable flow operation, the reference head points H_i shall be calculated by the following Formula (3):



$$H_i = \left(\frac{H}{100} \right)_i \cdot H_{100\%} \quad (3)$$



Where the values H corresponding to the N load points on the reference pressure control curve taken from Formula (1).

In the case of constant flow operation, the head points H are defined by the pump curve applied when defining $Q_{100} \%$, $H_{100} \%$.

For variable speed pump units on fixed flow, the test is at fixed speed with head points along the fixed nominal speed Q - H -curve. For fixed speed on variable flow the head cannot be adjusted to the reference pressure control curve and follows the pump unit Q - H -curve.

5.3 Calculation of $P_{1,avg}$

5.3.1 General

Measure the values Q_i , H_i and $P_{1,i}$ at each reference part load/over load point.

5.3.2 Pump units evaluated with the reference flow-time profile for constant flow operation

Based on the measured values of electric power input P_1 in the three load points (see Figure 1),

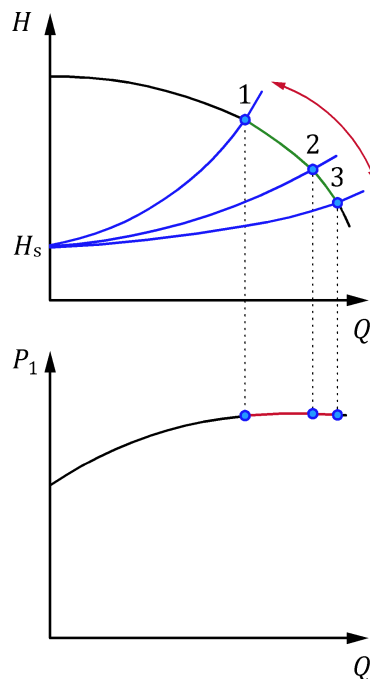


Figure 1 — Load points for constant flow systems – M1 and M3 (all pump units)

the weighted average of the electric power input $P_{1,avg,c}$ is calculated by Formula (4):

$$P_{1,avg,c} = \sum_{i=1}^3 \left[\left(\frac{\Delta t}{100} \right)_i \cdot P_{1,i} \right] \quad (4)$$

5.3.3 Pump units evaluated with the reference flow-time profile for variable flow operation

Figure 2 shows the measured values of electric power input P_1 in the four load points (see Figure 2) for variable flow operation:

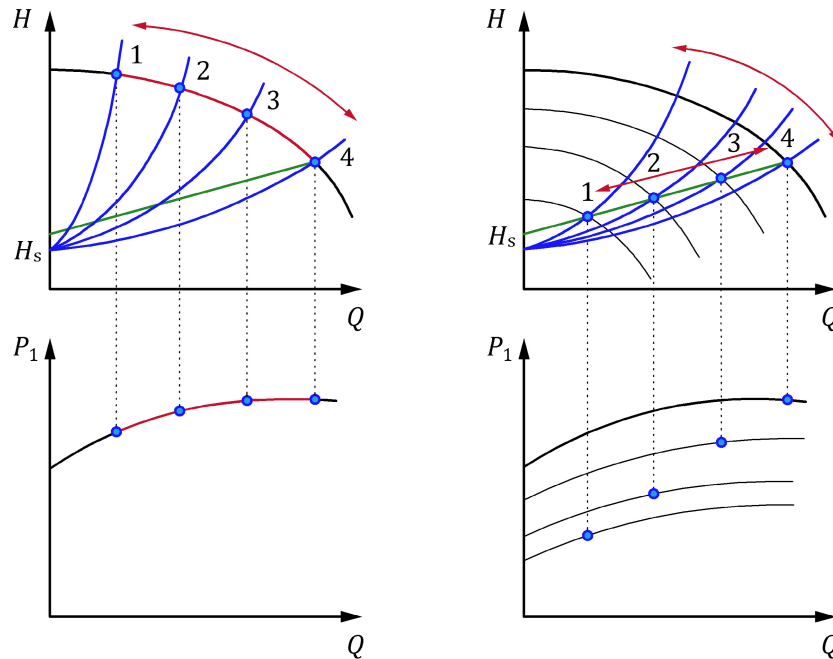


Figure 2 — Load points for variable flow operation – M2, M4 and M5 (fixed speed and variable speed pump units)

The steps to calculate $P_{1,avg,v}$ for variable speed pump units are as follows:

- 1) At each value of the adjusted and measured flow rate Q the measured pump head H_{meas} is compared to the target value H_i at the corresponding load point of the reference pressure control curve from Formula (3).
- 2) The measured electric power $P_{1,meas}$ at the flow rate Q_i at the given head of H_i shall be corrected (except for mode of operation M2) by Formula (5):

$$P_{1,corr} = \left(\frac{H_i}{H_{meas}} \right) \cdot P_{1,meas} \quad (5)$$

For fixed speed pump units in variable flow demand (mode of operation M2) $P_{1,corr}$ is equal to $P_{1,meas}$ and no correction is applied.

Then, the corrected electric power $P_{1,corr}$ at this flow rate Q is taken for the calculation of the weighted average of the electric power $P_{1,avg}$.

- 3) The weighted average of the electric power $P_{1,avg,v}$ is calculated by Formula (6):

$$P_{1,avg,v} = \sum_{i=1}^{i=4} \left[\left(\frac{\Delta t}{100} \right)_i \cdot P_{1,corr,i} \right] \quad (6)$$

5.3.4 Procedures for testing and evaluation of pump units with special pump types

5.3.4.1 General

For special pump types covered by the scope of this document, testing and evaluation according to 5.3.4.2 up to 5.3.4.3 shall be applied, respectively.

5.3.4.2 Pump units with twin head pumps (ESCCi with two impellers)

Pump units with twin head pumps shall be evaluated by incorporating one of the driver/impeller sets into an adequate single head pump casing of ESOB, ESCC or ESCCi type.

For calculating of the reference pump efficiency $\eta_{\text{ref,PJ}}$ the C-value from Table 4 shall be taken for the corresponding pump type and rotational speed.

5.3.4.3 Pump units with pumps according to more than one type definition

For pump units with pump types where more than one type definition is applicable the type of the pump casing shall determine which C value from Table 4 has to be taken.

6 Determination of the Energy Efficiency Index of pump units by the means of a semi-analytical model

6.1 General

Instead of determining the Energy Efficiency Index (EEI_V or EEI_C , later called *EEI-value*) by performing tests on complete pump units, their *EEI-value* can be determined by mathematical calculations based on a so-called semi-analytical model of the pump unit.

The mathematical model of the complete unit is composed of part models of the pump and of the electric components. The complete model considers the physical interactions of the components. For the calculation of *EEI-values* these models may partly or completely be used. Alternatively, mathematical models delivering at least the same accuracy of *EEI* values are permitted.

NOTE For example alternative mathematical models are permitted where the technology of components is not covered in this document or other mathematical (part-)models are available.

A model is called semi-analytical in this document if the mathematical correlations (= formulae) describe the performance in a principal form which reflects the underlying physical processes and influences, but needs a limited number of data (at so-called supporting points) which result from tests on the separate components. These data serve to “calibrate” the principal equations. In this sense, the model used for the pump is a semi-analytical one. On the other hand, the model describing the losses of a PDS (or the electric motor and the CDM it is composed of) are pure mathematical equations which serve to inter-/extrapolate losses in a certain range of load points on the basis of known values of these losses at a limited number of supporting load points (specified by standard(s)).

The models describe the relation between physical input and output quantities (= performance variables) of the components as well as of the complete unit by mathematical equations. These are for example the dependence of the pump head H on pump flow rate Q and rotational speed n or the dependence of the power losses $P_{V,\text{PDS}}$ of a Power Drive System (PDS) on shaft torque T and rotational speed n .

While the result of tests to determine the *EEI-value* of an individual test pump unit shows generally a (total) measurement uncertainty, the accuracy of any value (for example the *EEI-value*) determined mathematically by the means of models is dependent on the magnitude of the model uncertainties.

Model uncertainties are the maximum possible deviations (with a probability of typically 95 %) from the calculated values of the model's output variables from the correct values of the real component output variables for the same values of the input variables. Their magnitude depends on the assumptions, approximations and simplifications which determine the quality and correctness of the models.

The magnitude of uncertainties of the models which can serve to determine the *EEI*-value of an individual pump unit or of the mean *EEI*-value of a type size of pump units and which are described in this document are given in Annex D.

The method described in this clause is applicable to pump units:

- consisting of components (pump and motor system) of which the particular performance characteristics are known within the relevant range of load points – at least at a limited number of operating points (see also Annex B) - including possible effects of interaction between components (for example additional losses of electric motors fed by a CDM),
- enabling to set the operating point of maximum unit efficiency η_{unit} and the corresponding values of $Q_{100} \%$ and $H_{100} \%$ (according to their definition in Clause 4) at constant stator frequency.

6.2 The semi analytical model of the pump

The semi-analytical model which is needed to describe the pump performance consists of the 3 mathematical functions $H/H_{\text{BEP,N}} = f(Q/Q_{\text{BEP,N}}, n/n_{\text{N,PU}})$, $T/T_{\text{BEP,N}} = f(Q/Q_{\text{BEP,N}}, n/n_{\text{N,PU}})$ and $P/P_{\text{BEP,N}} = f(Q/Q_{\text{BEP,N}}, n/n_{\text{N,PU}})$, see Formulae (10) and (11).

$Q_{\text{BEP,N}}$, $H_{\text{BEP,N}}$, $T_{\text{BEP,N}}$ and $P_{\text{BEP,N}}$ are the flow rate, the pump head, the shaft torque and the shaft power, respectively, at the best efficiency point (BEP) of the pump at its nominal rotational speed $n_{\text{N,PU}}$.

In the model, the dimensionless characteristic $H/H_{\text{BEP}} = f(Q/Q_{\text{BEP}})$ at $n = n_{\text{N,PU}}$ is approximated by a 3rd degree polynomial:

$$\frac{H}{H_{\text{BEP}}} = a_H \cdot \left(\frac{Q}{Q_{\text{BEP}}} \right)^3 + b_H \left(\frac{Q}{Q_{\text{BEP}}} \right)^2 + c_H \cdot \frac{Q}{Q_{\text{BEP}}} + d_H \quad (7)$$

The dimensionless characteristic $P/P_{\text{BEP}} = f(Q/Q_{\text{BEP}})$ at $n = n_{\text{N,PU}}$ is also approximated by a 3rd degree polynomial:

$$\frac{P}{P_{\text{BEP}}} = a_P \cdot \left(\frac{Q}{Q_{\text{BEP}}} \right)^3 + b_P \left(\frac{Q}{Q_{\text{BEP}}} \right)^2 + c_P \cdot \frac{Q}{Q_{\text{BEP}}} + d_P \quad (8)$$

In the Formulae (7) and (8), a_H to d_H are the polynomial coefficients for the dimensionless Q - H -characteristic and a_P to d_P are the polynomial coefficients for the dimensionless characteristic.

The coefficients have to be determined mathematically in such a way that the Formulae (7) and (8) are best-fit functions for a number k of operating points located on the mean dimensionless characteristics $H/H_{\text{BEP}} = f(Q/Q_{\text{BEP}})$ and $P/P_{\text{BEP}} = f(Q/Q_{\text{BEP}})$ of the pump, respectively, at $n = n_{\text{N,PU}}$. These points serve as supporting points for the calibration of the pump model. The Formulae (7) and (8) shall fulfil the condition of “least squares”.

The actual values at the supporting points result from tests and evaluations on the respective pump size and shall represent mean values of the size. Generally, the choice of a suitable number k of supporting points used to determine the best-fit functions:

- the number of supporting operating points should at least be $k = 5$,
- the supporting operating points shall cover at least the range of relative flow rate $0,1 \leq (Q/Q_{\text{BEP}}) \leq 1,1$.

NOTE It is important to realize that the mean characteristics of the pump size and the supporting operating points taken therefrom describe the mean performance quantities x (i.e. Q , H , P and T) of the pump size only within a band $x_{\text{mean}} \pm t_{x,\text{tot}}$. These total tolerances $t_{x,\text{tot}}$ of the performance quantities and characteristics result from manufacturing performance tolerances $t_{x,\text{man}}$ as well as from measurement uncertainties e_x . Methods to determine the mean values and the total tolerances are described in EN 16480.

A method to determine the polynomial functions $H/H_{\text{BEP}} = f(Q/Q_{\text{BEP}})$ and $P/P_{\text{BEP}} = f(Q/Q_{\text{BEP}})$ of the pump on the basis of only 3 supporting operating points which result from the determination of the *MEI*-value of the pump according to EN 16480 together with 2 additional supporting points resulting from empirical correlations is described in Annex B.

At $n = n_{\text{N,PU}}$, a polynomial function with the same polynomial coefficients a_p to d_p is valid for the relative torque T/T_{BEP} .

$$\frac{T}{T_{\text{BEP}}} = a_p \cdot \left(\frac{Q}{Q_{\text{BEP}}} \right)^3 + b_p \cdot \left(\frac{Q}{Q_{\text{BEP}}} \right)^2 + c_p \cdot \frac{Q}{Q_{\text{BEP}}} + d_p \quad (9)$$

For operating (= load) points according to the reference load flow profiles and to the reference pressure control curves specified in Clause 4, the range of speed variation is typically $0,7 \leq n/n_{\text{N,PU}} < 1,05$.

Within this range of the relative rotational speed $n/n_{\text{N,PU}}$, the relative characteristics can be written for variable rotational speed $n/n_{\text{N,PU}}$ based on the laws of hydrodynamic similarity:

$$\frac{H}{H_{\text{BEP,N}}} = a_H \cdot \frac{\left(\frac{Q}{Q_{\text{BEP,N}}} \right)^3}{\left(\frac{n}{n_{\text{N,PU}}} \right)} + b_H \cdot \left(\frac{Q}{Q_{\text{BEP,N}}} \right)^2 + c_H \cdot \left(\frac{Q}{Q_{\text{BEP,N}}} \right) \cdot \left(\frac{n}{n_{\text{N,PU}}} \right) + d_H \cdot \left(\frac{n}{n_{\text{N,PU}}} \right)^2 \quad (10)$$

$$\frac{T}{T_{\text{BEP,N}}} = k_{\text{corr}} \cdot \left[a_p \cdot \frac{\left(\frac{Q}{Q_{\text{BEP,N}}} \right)^3}{\left(\frac{n}{n_{\text{N,PU}}} \right)} + b_p \cdot \left(\frac{Q}{Q_{\text{BEP,N}}} \right)^2 + c_p \cdot \left(\frac{Q}{Q_{\text{BEP,N}}} \right) \cdot \left(\frac{n}{n_{\text{N,PU}}} \right) + d_p \cdot \left(\frac{n}{n_{\text{N,PU}}} \right)^2 \right] \quad (11)$$

$$\frac{P}{P_{\text{BEP,N}}} = k_{\text{corr}} \cdot \left[a_p \cdot \left(\frac{Q}{Q_{\text{BEP,N}}} \right)^3 + b_p \cdot \left(\frac{Q}{Q_{\text{BEP,N}}} \right)^2 \cdot \left(\frac{n}{n_{\text{N,PU}}} \right) + c_p \cdot \left(\frac{Q}{Q_{\text{BEP,N}}} \right) \cdot \left(\frac{n}{n_{\text{N,PU}}} \right)^2 + d_p \cdot \left(\frac{n}{n_{\text{N,PU}}} \right)^3 \right] \quad (12)$$

Depending on the impeller diameter D_{imp} and the rotational speed n of the pump, it may be necessary to apply a correction to the relative shaft torque $T/T_{\text{BEP,N}}$ and to the relative shaft power $P/P_{\text{BEP,N}}$ at $n/n_{\text{N,PU}} < 1$. This correction considers slight deviations from the hydrodynamic similarity when the rotational speed is reduced from the nominal value. Within the relevant range the following approximate correction factor k_{corr} can be applied:

$$D_{imp}^2 \cdot \frac{n}{60} \geq 1 \Rightarrow k_{corr} = 1$$

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$$D_{imp}^2 \cdot \frac{n}{60} < 1 \Rightarrow k_{corr} = \left(\frac{n}{n_{N,PU}} \right)^{-0,15} \quad (13)$$

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Formula (13) uses D_{imp} in [m], n in [min^{-1}].

Near the upper limit of the range of specific speed n_s of the pumps specified by the scope of this document, the outer diameter of the impeller blading may vary along the outlet edge of the impeller blades. In such cases, in Formula (13) the smallest outer impeller diameter which is normally the diameter at the back shroud $D_{imp,back}$ has to be taken as the impeller diameter D_{imp} .

6.3 Pump units in fixed speed operation

6.3.1 General

The method described in this sub-clause is valid for pump units with an asynchronous electric motor of the cage-induction type. For this motor type, the rotational speed n is slightly smaller than the synchronous speed n_{sync} which corresponds to the grid frequency. The difference between synchronous speed and actual rotational speed n (described as the so-called slip s in percentage of the synchronous speed) is dependent on the motor type and size and additionally on the motor load. The method takes into account the small variations of the rotational speed of the pump unit with the varying pump shaft power and shaft torque.

In Figure 3 the structure of the model is shown. The electric power input P_1 from the grid is transformed by the electric motor to the mechanical motor output power P_2 . The mechanical motor output power P_2 is transmitted via mechanical coupling to the pump input power P which transforms this mechanical input (= shaft) power P into the hydraulic power P_{hyd} . The hydraulic power P_{hyd} is transmitted to the fluid in the hydraulic circuit.

In Figure 3 single sided arrows represent the power transmission while bidirectional-arrows represent the physical interactions with the corresponding physical quantities.

The grid and the electric motor interact via the electric quantities voltage U and current I . The internal interaction of the components electric motor and pump happens via the mechanical quantities rotational speed n and torque T . The pump interacts with the hydraulic circuit via the hydraulic quantities flow rate Q and pump head H .

The demand of flow rate Q and head H determines the corresponding mechanical pump input power P which includes besides the hydraulic power P_{hyd} the internal power losses of the pump $P_{L,PU}$. The electric power input P_1 covers the shaft power $P_2 = P$ and additionally the internal power losses of the electric motor $P_{L,M}$.