Technical Paper

Session: 4 - 3

Session Name: Eco Design Challenges

Development of a Standardized Approach to Assess the Energy Efficiency of Booster Pump Units in the Sense of an Extended Product

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Summary

With regard to the so called extended product approach (EPA), an appropriate methodology to qualify respectively verify these extended products has been successfully developed at the Institute for Fluid Systems of Technische Universität Darmstadt – supported by Europump – for single pump units. The EPA is a measure to meet the energy related products (ErP) and energy using products (EuP) requirements of the European Commission.

Based on the experience of this work Europump decided to expand the EPA also to booster pump units, which normally consist of multiple pumps as well as further hydraulic and electric components to ensure the specific demands of pressure boosting within buildings. A characteristic rating is needed to compare and quantify the energy efficiency of booster pump units in a standardized way. The development of a draft standard proposal for further regulation is the final objective of this work. As a result the energy efficiency index (EEI) as a normalized weighted average of the electrical input power for a booster pump unit operating at different duty points at part load is introduced. A standardized load-time profile and a pressure control curve are defined in order to compare lifetime efficiency and part load behaviour. The EEI will be determined using both an experimental and semi-analytical approach.

Main task of the experimental work is the development of a measurement procedure for the EEI determination, which can be summarized as a realization of sensitivity studies in order to deduce all major effects on the EEI for a subsequent standard elaboration. This includes the definition of needed accuracy and acceptable tolerances of flow-adjustment and used sensors as well as the examination of parameters affecting the power consumption of the booster pump unit. Besides, steady state operation for each duty point has to be guaranteed. A method for non-adjustable duty points within the given constraints has to be implemented which is attended by the exertion of penalties in EEI for overshooting. The tasks of the Institute for Fluid Systems of Technische Universität Darmstadt are the development and neutral assessment of all required measurement procedures.

Besides the experimental work, a semi-analytical approach is developed which allows calculating the electrical input power and thus the EEI with reduced experimental effort in future. The resulting semi-analytical model (SAM) is based on empirical data for frequency converters, motors and pumps as well as analytical laws describing the physics of booster system behaviour. A further advantage of SAM is the possibility of systematic determination of EEI values for booster units consisting of components delivered by different manufacturers.

1. Introduction

The energy consumption of water pump systems in the European Union adds up to 137 TWh per annum [1]. This corresponds to 4 % of the total energy production of 3400 TWh per annum. According to the European Ecodesign Directive, the aim of the EU is to save energy of energy using (EuP) and energy related products (ErP) by establishing minimum efficiency requirements. In the context of a Product Approach (PA), efficiency requirements of single products, i. e. frequency converter, motor and pump, are demanded. These requirements are already set for water pumps and electric motors in [2] and [3]. As the focus of these requirements lies on the energy efficiency at a nominal operating point, a potential part load behaviour will not be considered. Introducing the Minimum Efficiency Index (MEI) for pumps and the International Efficiency (IE) classes for electric motors, an increased energy saving potential of 2 % for pumps [2] and 11 % for electric motors [3] is indicated. Combining the interaction of single products including part load behaviour leads to the so called Extended Product Approach (EPA). The quantitative measure to rate energy efficiency of single pump or booster pump units is introduced as Energy Efficiency Index (*EEI*) which will result in an energy saving potential of 25 % [4]. In this context a booster pump unit means an assembly of multiple clean water pump units and components necessary to control pressure or provide flow in open loops inside buildings. The application of the EPA to single pump units has already been assessed at TU Darmstadt [5]. The results of this work lay the foundation of a standard to quantify the energy efficiency for single pumps. As a continuation of this work, the energy efficiency of booster pump units is being determined in the frame of this paper.

This paper describes an experimental approach to assess the *EEI* for booster pump units. This comprehends fixed speed units which do not comprise frequency converters and variable speed units including variable speed driven motors. Mixed compositions, so called flying converter compositions are in the scope as well. For future *EEI* measurements, clearly defined instructions need to be specified. These instructions will for instance include definitions regarding the measurement setup or needed accuracy of sensors. Measurements that are carried out at our institute will identify the influence of different parameters on the *EEI* which will be needed in further steps to define measurement instructions. The aim of this work is the identification and assessment of influencing parameters on *EEI*.

2. Energy-Efficiency-Index

As a basic feature of the EPA, a realistic consideration of the particular application of booster pump units needs to be known. This includes both a load-time profile and a pressure control curve. To enable comparability between different booster pump units despite the different applications, which exist market-wide, a standardized load-time profile, shown in Table 1, is specified. Indicated weighted time represents the fractions Δt_i of the total operation time t_{tot} at which the booster pump unit is operated at the corresponding duty point i. The development of this load-time profile is based on measurements performed using booster units inside real buildings [6] and is internationally accepted as being a representative study.

Table 1: Duty points for the determination of EEI of booster units.

Duty point i	1	2	3	4	5	6	7	8	9	10
$Q_i/Q_{100\%}$	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
$\Delta t_i/t_{\text{tot}}$	0.06	0.21	0.26	0.19	0.12	0.06	0.04	0.03	0.02	0.01

In order to consider part load behaviour of booster pump units, ten duty points characterized by the rated flow rates $Q_i/Q_{100\%}$ are specified as shown in Table 1. The subscript 100% denotes the nominal operating point of the booster unit which is defined by the maximum hydraulic power output $P_{\text{hyd},100\%} = \varrho g H_{100\%} Q_{100\%}$ at its nominal rotational speed $n_{100\%}$.

In addition to the load-time profile, a pressure control curve for booster pump units is defined [6] by

$$\frac{H_i}{H_{100\%}} = 0.75 + 0.25\frac{Q_i}{Q_{100\%}} \tag{1}$$

and takes into accouont the reduction of the static head H at decreasing values of flow rate Q. This is due to the fact that in real application some static head needs to be maintained even for vanishing flow rates. Both, load-time profile and pressure control curve are visualized in Figure 1.

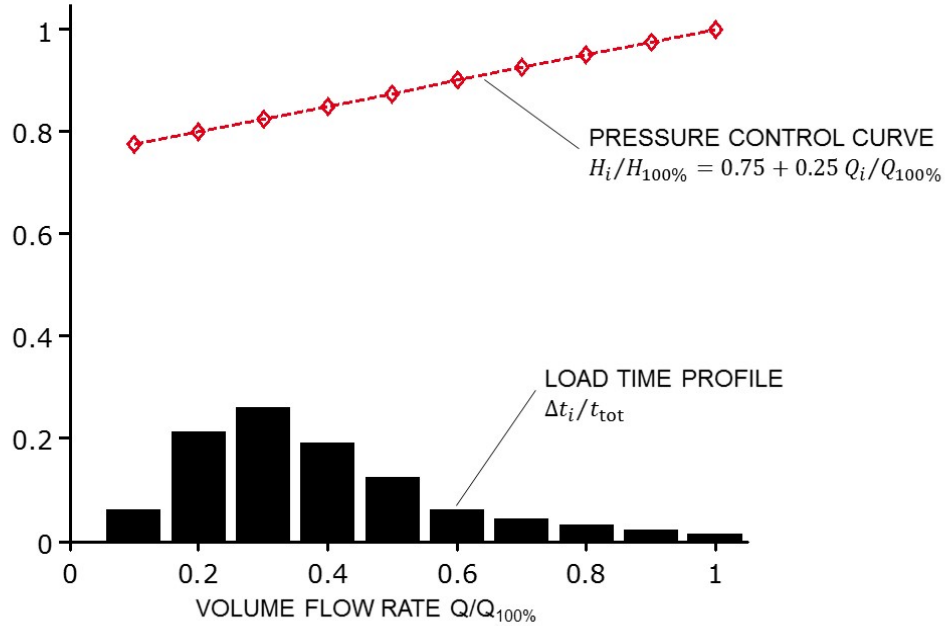

Figure 1: Standardized pressure control curve and load-time profile for booster pump units.

The quantitative measure to rate energy efficiency of booster pump units is introduced as *EEI* which is a dimensionless value defined by

$$EEI := \frac{P_{1,\mathrm{avg}}}{P_{1,\mathrm{ref}}}. \tag{2}$$

Please note that this definition has a preliminary status. The final *EEI* calculation method including a final definition will be published in a corresponding standard.

In equation 2, $P_{1,\mathrm{avg}}$ denotes the sum of the electrical input power values $P_{1,\mathrm{i}}$ at each duty point at the pressure control curve from equation 1 with individual weighted time fraction $\Delta t_i/t_{\mathrm{tot}}$ from Table 1:

$$P_{1,\mathrm{avg}} = \sum_{i=1}^{10} \frac{\Delta t_i}{t_{\mathrm{tot}}} P_{1,i}. \tag{3}$$

For fixed speed booster pump units the electrical input power equals the power fed to the motor, for variable-speed booster units the electrical input power equals to the power fed to the frequency converter. The value $P_{1,\mathrm{ref}}$ in equation 2 represents an input power of a reference virtual booster unit with identical nominal data, i. e. ($Q_{100\%}$, $H_{100\%}$)-point. It is calculated based on the maximum hydraulic power output $P_{\mathrm{hyd},100\%}$ of the considered booster pump unit including efficiencies of pump, motor and converter. The latter are determined according to existing product-specific efficiency standards [5], [7]. This definition of *EEI* allows to compare booster pump units regarding their nominal data and part load efficiency representing a real life application. According to equation 2, booster pump units with lower *EEI* values consume less energy to fulfil the same requirements in terms of identical load profiles than booster pump units with higher *EEI* values. Hence, smaller *EEI* values represent more energy-efficient units.

3. Determining the EEI

The *EEI* can be determined using an experimental or a so called semi analytical approach. Main focus of this paper is the experimental work. The experiments at TU Darmstadt will provide fundamentals for a future standard being applied on booster pump units to quantify the energy consumption and to indicate an *EEI*.

Experimental Approach

Applying an experimental approach, the *EEI* will prospectively be measured in test rigs or real life applications. One of the main objectives of the experimental project carried out by TU Darmstadt is the declaration of measurement instructions. These are supposed to enable a comparable measurement procedure resulting in comparable *EEI* values during the industrial application of the experimental approach later on. The development of this measurement procedure is validated experimentally. A sketch of the closed loop test rig at the institute is shown in Figure 2. This test rig is composed of a three-pump booster pump unit and a control unit allowing to switch on and off up to three frequency converters. This is equivalent to a selection of different modes of operation i. e. fixed speed (no frequency converter), variable speed (three frequency converters) and flying converter (one frequency converter). The nominal hydraulic data of each pump is $Q_{100\%}$ = 3.29 m^3/h and $H_{100\%}$ = 42.43 m. The adjustment and measurement of the flow rate Q is realized by a control valve and a flow meter respectively. A water tank allows to regulate the input pressure by a compressed air input. The input power P_1 measurement is located at the supply line of the control unit. To determine the total head H of the booster pump unit, a differential pressure sensor is installed between the suction- and pressure-side manifolds. Further sensors allow to monitor water and motor temperatures, rotational speed and input pressure inside the water tank.

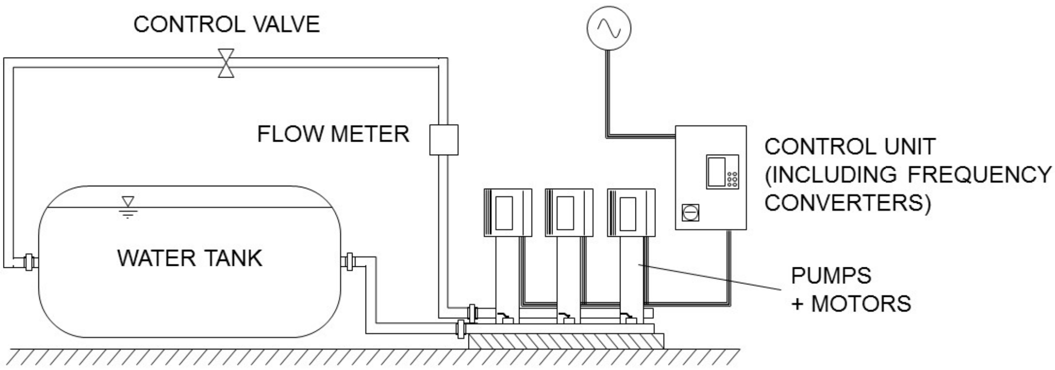

Figure 2: Experimental setup for EEI measurements at TU Darmstadt.

A list of parameters influencing the *EEI* has been compiled to be able to classify the impact of each parameter. Besides the parameters which do not have a significant effect on the *EEI*, main parameters influencing the *EEI* have been figured out to be the following:

- mode of operation,
- order of measurement points,

- accuracy of flow and head adjustment.

The mode of operation of the booster pump unit, i. e. fixed speed, variable speed or flying converter, is an influencing parameter on the *EEI*. Fixed speed units do not have the possibility to reduce the rotational speed and therefore cannot follow the predefined pressure control curve from equation 1 but follow its pump characteristics when flow rate is throttled. For increasing flow rate the total head drops and the only way for fixed speed booster units to maintain the setpoint pressure at each duty point is to switch on one additional pump. This effect is visualized in Figure 3 with the pressure control curve being indicated as a dashed line. Switching points for fixed speed are identified between duty points 3 to 4 and 7 to 8, respectively. Consequently the input power consumption at each duty point is higher compared to variable speed or flying converter mode of operation which results in a higher *EEI* considering equation 2. Variable speed and flying converters provide the opportunity to change the rotational speed of at least one pump. Hence, they are able to follow the pressure control curve resulting in a lower *EEI* compared to fixed speed booster units.

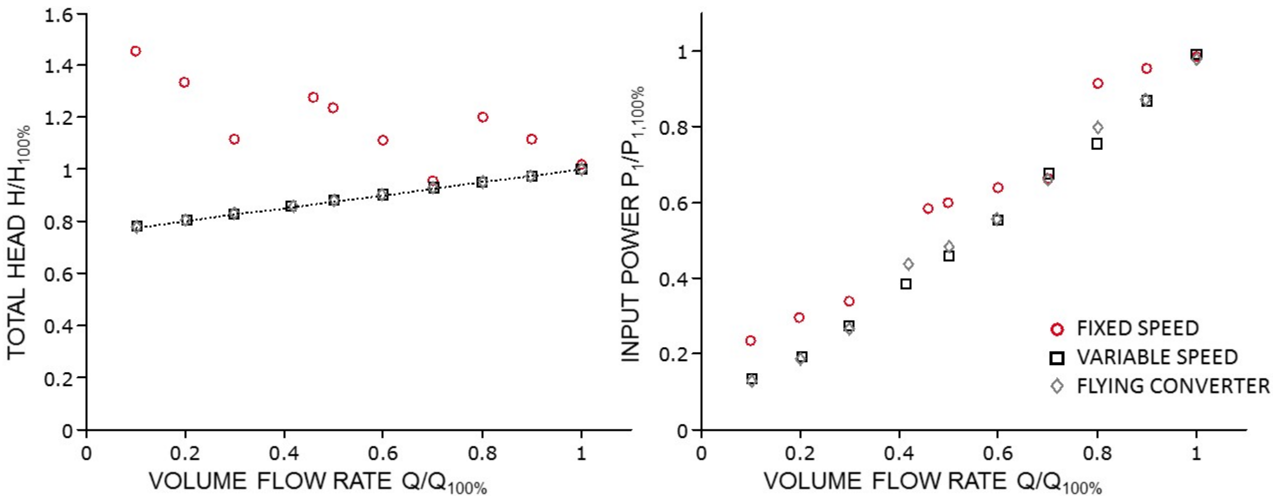

Figure 3: Comparison of total head and input power at the ten duty points at increasing flow rate for different modes of operation fixed speed, variable speed and flying converter.

Depending on the order of measurement points of the ten duty points from Table 1, different numbers of pumps running lead to different input power consumption. This effect is most distinct for a fixed speed booster mode of operation, which is shown in Figure 4. Starting the measurement with duty point 1 and ending it with duty point 10 is denoted increasing flow rate, vice versa will be decreasing flow rate. Only for the three duty points 8, 9 and 10 all three pumps are running independent of the order of measurement points in this case. At lower flow rates the booster pump unit is operating with two pumps for decreasing flow rate even though one pump would provide the requested head. This effect is due to the switching hysteresis implemented in the control unit of the booster.

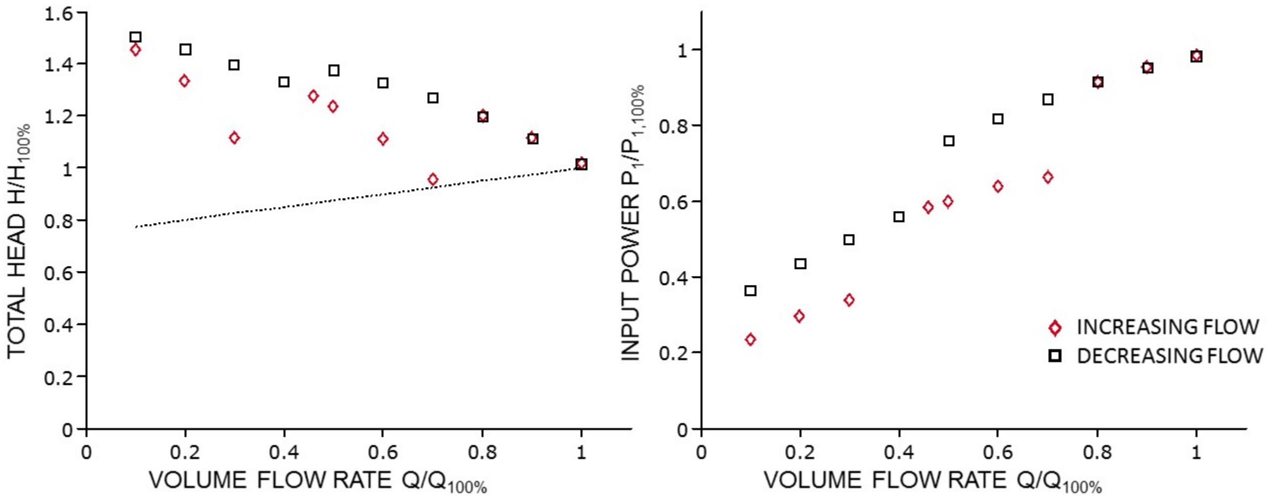

Figure 4: Comparison of total head and input power at the ten duty points at fixed speed mode of operation for increasing and decreasing flow rate.

The required accuracy of flow adjustment, i. e. the range of tolerable inaccuracy of the flow rate or total head, has to be defined for future *EEI* measurements. Adjusting slightly inferior values for both, flow rate or head at each duty point leads to a lower input power consumption which will result in a lower *EEI*. The question is which range of flow and head adjustment is tolerable for *EEI* measurements. Regarding head undershooting, the setpoint pressure defined by equation 1 will prospectively be penalized. This penalty is applied if a measured head H_{meas} is smaller than the corresponding setpoint H_{set} from equation 1. The power consumption is scaled in such a way that an undershooting will be rated as an overshooting of the same difference in head. For *EEI* determination, the penalized input power

$$P_{1,\mathrm{corr}} = \left(2\frac{H_{\mathrm{set}}}{H_{\mathrm{meas}}} - 1\right) P_{1,\mathrm{meas}} \qquad (4)$$

is used replacing $P_{1,\mathrm{meas}}$ at the corresponding duty point. The setpoint H_{set} is calculated setting the flow rate Q_i equal to the measured flow rate Q_{meas} in equation 1. Not attaining the setpoint will consequently rise the penalized input power consumption and result in a higher *EEI*. Regarding flow rate undershooting, no penalty exists which is why the accuracy of flow adjustment plays an important role for *EEI* measurements. By systematically adjusting a deviation of 5 % $Q_{100\%}$ flow rate below or above each load point at the test rig, the sensitivity of flow rate adjustment on the *EEI* is assessed. The flow rate is compared to measurements with 0 % $Q_{100\%}$ flow rate deviation which correspond to the exact value for each duty point. This analysis is performed for every mode of operation and the results are similar and visualized in Figure 5. Consistently underrating the flow rate reduces the *EEI* of 2 % per 1 % $Q_{100\%}$ flow rate gap between setpoint and current measurement point and overrating the flow rate will rise the *EEI* for the same magnitude. This result is fundamental for future *EEI* measurement instructions regarding permissible flow rate adjustment tolerances and its impact on *EEI* accuracy.

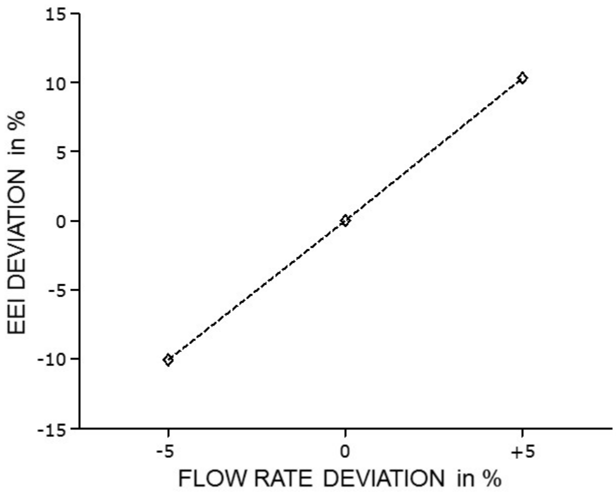

Figure 5: Influence of flow rate adjustment deviation on the EEI.

The parameters listed above do have significant effects on the *EEI*. In contrast to that, the following parameters have been figured out to be less important influences on the *EEI*.

Measurements revealed that no significant influence, i. e. higher than measurement uncertainties, of water temperature ϑ_w on the *EEI* is identifiable in the range 20 °C < ϑ_w < 25 °C. Varying the input pressure p_in in the range 0 bar < p_in < 1 bar overpressure compared to the environment does not show any influence on the *EEI* as well for identical differential pressure. This is valid only for NPSH requirements being fulfilled within the entire inlet pressure range, which was the case at our measurements.

As the motor efficiency also depends on the winding temperature, its effect on the *EEI* is being investigated. To obtain information about to which extent the motor temperature ϑ_m influences the *EEI*, the booster pump unit is operated at the ($Q_{100\%}$, $H_{100\%}$)-point and the total input power $P_{1,100\%}$ is measured over time. Initial condition of this experiment is the cold motor state, i. e. the motor temperature equals ambient temperature. The temperature sensors are placed inside the motor casing and do not quantify the motor winding temperature but represent a comparable value as increasing or converging winding temperature will result in increasing or converging behaviour of ϑ_m. This setup reveales a negligible influence, i. e. smaller than measurement uncertainty, of ϑ_m on $P_{1,100\%}$. It can be derived that other duty points at part load show a similar behaviour and are not influenced by ϑ_m. Nevertheless, converging of the motor temperature over time is observed and a run-in-phase before starting the measurement is recommended.

To evaluate the change of booster pump characteristics over time due to potential run-in-time of the bearings or erosion, the hydraulic booster pump curve including input power consumption is measured once each week during the project to monitor potential deviations. No significant change of the input power at the load points or the hydraulic curve is observed.

Semi-Analytical Approach
Besides the experimental approach, a so called semi analytical model (SAM) is developed [8]. This model allows the estimation of the *EEI* of booster pump units in a conservative way based on empirical data. The SAM can be applied if an experimental determination is not possible which can be the case for installer markets, i. e. for units consisting of components delivered by different manufacturers. For the determination of the *EEI* for single pump units, a SAM has successfully been implemented [5]. As the main focus of this paper lies on the description of the experimental approach, no further specification will be made here.

4. Conclusion

The basics of *EEI* calculation are illustrated in this paper. For a future standard, the determination of the *EEI* will be an important point which is why influencing parameters for an experimental approach are being investigated. If no experimental measurements are possible, a semi-analytical approach will assess the *EEI* in a conservative way based on empirical data. The experimental approach needs to be specified in order to obtain comparable *EEI* values for booster pump units. Parameter studies were performed to detect influential quantities which need to be specified for prospective *EEI* measurements.

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