Proper sizing of circulation pumps

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Abstract
The paper describes the preliminary results from field tests of replacing various types of old pumps used for circulating water in heating systems in single- and double-family houses with new types of pumps. The tests were carried out in Denmark for the Danish Electricity Savings Trust, but the results can be applied to Europe in general. Despite the small sample of houses involved in the test, 15 houses, some rather safe conclusions can be drawn from the results, which showed that newly developed pumps with power consumption around 5-8 W, can perform the task of circulating the water sufficiently to keep the houses satisfactorily warm during the heating season of the test. The old replaced pumps used 5-10 times more power. In Europe alone, a gradual replacement of the present vastly oversized pumps with such small but sufficient pumps can save the construction of 17 large power plants as well as their pollution during operation. Policy measures are proposed of how to ensure that in the future only such energy saving pumps are installed. Furthermore, on the basis of the historic experiences with circulation pumps some conclusions are drawn on how to investigate, develop and market new technologies in general.

Introduction
Already in the 1970's investigations at the Technical University of Denmark showed that circulation pumps for central heating systems in small houses were heavily oversized and accounted for significant power consumption, typically requiring 65 W (Nørgård 1979). Actual hydraulic power needed was found to be as low as 1-2 W. It was at that time suggested to develop small pumps with 2 Watt pumping capacity and an efficiency of 15 %, so the power consumption would amount to less than 13 W or 20 % of what was typically used at that time. The unnecessarily large power consumption was due to: 1) Vastly oversized pumps, 2) Low efficiency of the pumps, and 3) Lack of demand control of pumps that often ran at full capacity the whole year. In the light of these facts it was also later recommended to develop small but relatively effective pumps with power consumption of 5-10 W (Nørgård 1989). Subsequently the circulation pumps on the market gradually improved, financially supported by the Danish Government. Later, however, it became clear that the development had focused on pumps with automatic capacity control by variable-speed motors, not on properly sized pumps (Staubli et al 1996). Technically there had been no barriers to develop a 5-10 W pump with a conventional (non-controllable induction) motor. Around 1990, research at the Technical University ETH-Z in Zürich began investigating the options for better pumps and during the next couple of years a prototype combining a suitable small capacity and a high efficiency was developed. The efficiency reached up to 40 % compared to normally 5-10 % (Staubli et al 1996, Nipkow 1995). The development took place in cooperation with a pump producer, named Biral, and was supported financially by the Swiss Governments Energy Authority.

On the 1st of January 2006 the new EU energy performance directive was implemented in Danish legislation. This implies that power consumption for circulation pumps in the future shall enter into the calculation of buildings energy efficiency requirements. Denmark has during 2005 modified the energy regulations in the Building Code for new houses with the purpose of lowering the energy frame by 25–30 %. This frame consist of: 1) energy consumption used for heating, *plus* 2) electricity, multiplied by a factor 2.5, used by the permanently installed electric devices. This means that power for circulation pumps can account for a significant part of the total energy frame allowed.

Simultaneously pumps with more suitable capacities, higher efficiencies and capacity control have entered the market. To turn these possibilities into real electricity savings the Danish Electricity Savings Trust is running a campaign to get attention to the right choice of circulation pumps. In connection with this campaign the Department of Civil Engineering at the Technical University of Denmark (BYG.DTU) has carried out a project, investigating the need for electricity for circulation pumping in both new and existing single- and double-family houses. When BYG.DTU in 2005 started a series of field tests of different circulation pumps and decided to include the newly developed, properly sized Biral MC 10 pump, other brands of pumps were almost ready for production of similarly small capacity pumps, amongst others Grundfos, Wilo and Smedegaard, and these pumps were therefore with a little delay included in the project (Tommerup and Nørgård 2006).

This paper describes investigations of the present and future need for electricity for circulation pumps in central heating systems used in one- and two -family houses, including calculations and measurements of this present need for electricity and evaluation of the future need. Recommendations concerning energy saving circulators are stated in relation to the new EU energy directive from 2006 (Tommerup and Nørgård 2006).

Earlier investigations on electricity savings from better circulation pumps have focused on the problem of getting pumps with automatic control and somewhat improved efficiencies disseminated (EU SAVE II 2001), not on proper sizing of the pumps, which is the main feature of this paper.

Calculations of the need for pumping power

The result of calculations of the power consumption for circulating central heating water in typical Danish single- and double-family houses are described below, including the basis for calculations of power consumption.

THEORETICAL FOUNDATION FOR CALCULATION OF POWER CONSUMPTION

The characteristics of circulation pumps and heating systems are normally described in a diagram, see Figure 1, showing the pump pressure as a function of the flow (pump characteristic) and in one showing the pressure drop in the heat distribution systems as a function of the flow (system characteristic). The intersection point is the operation point, which indicates the flow the pump is able to circulate in the heating system.

The non-controllable pump results in a rising pump pressure (P_{1-x}) at falling flow rate (q_1-q_x). The automatically controlled pump with proportional pressure regulation results in a declining pump pressure at a falling flow rate as the pump speed is decreased from n_1 to n_x. As the hydraulic power consumption is equal the product of pressure and flow (see below) the latter mentioned pump type will result in lower electricity consumption.

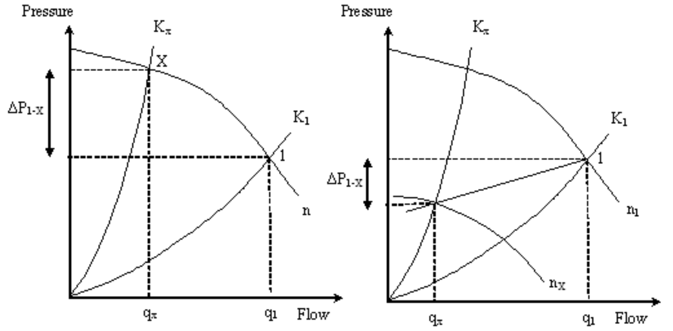

Figure 1. *Sketch of pump and system characteristics for a non-controllable pump (left) and an automatically controlled pump with so-called proportional pressure regulation (right).*

The necessary pump pressure is approximately equal to the pressure drop Δp in the heat distribution system. The electric power consumption P_{el} [W] of the pump motor is given by:

$$P_{el} = \frac{\Delta p \cdot q_v}{\eta_p \cdot \eta_{mo}} \qquad (1)$$

where q_v is the flow rate [m^3/s], and η_p and η_{mo} are the pump efficiency and the electric motor efficiency respectively. $\Delta p \cdot q_v$ is the hydraulic power P_h .

NECESSARY FLOW

The necessary flow q_v [m^3/h] (m^3/s = $q_v \cdot 1/3600$), determined by the maximum heating power Φ [kW] and the minimum fall in temperature ΔT [K], is defined as:

$$q_v = 0,86 \cdot \frac{\Phi}{\Delta T} \qquad (2)$$

The factor 0.86 is a conversion factor regarding the physical properties of water. The necessary heating power has been estimated for existing Danish single- and double-family houses, indicating that the major part of these houses have heat load demands of 5-10 kW while the larger and poorest insulated houses would have demands of up to 20 kW. The heat load demand in new houses is about 3 kW. Calculations were carried out for heating demands of 5, 10 and 20 kW, see Table 1. At the same time the cooling, i.e. the temperature drop, of the circulated water was estimated, and the conclusion was that it would be reasonable to consider a cooling of 30 K for district heating and a maximum cooling of 15 K for heating systems with a gas or oil boiler. The rather small design cooling of water in heating systems with gas or oil boiler (with a small water content) is primarily required to secure a sufficient flow in the boilers' heat exchanger as the heat exchanger otherwise will be thermally overloaded, which would reduce the lifetime of the boiler.

NECESSARY PUMPING PRESSURE

The necessary pump pressure is determined as the pressure drop to the farthest radiator and back to the pump. This is often known as the most unfavourable circuit. The resistance include the pressure drop in pipes, bends, heat exchangers, radiator valves and radiators. It is assumed that the dominating contributions come from heat exchanger, radiator valve and heating pipes. A standard heat exchanger has a pressure drop of 1-4 kPa, so on the safe side 4 kPa is used in the calculations. A pressure drop across the valve of 5 kPa is assumed, thereby ensuring a good valve function and flow distribution. The pressure drop ΔP_r [Pa] in straight pipes can be calculated from the following equation:

$$\Delta p_r = \lambda \cdot \frac{\rho \cdot v^2 \cdot L}{2 \cdot d} \qquad (3)$$

Where λ is the coefficient of friction, ρ is the density of water [kg/m^3], v is average velocity [m/s], L is the length of the pipes [m], d is the hydraulic parameter (internal diameter) of pipe [m]. The coefficient of friction depends on the nature of the water flow expressed by Reynolds number, Re, and the roughness of the inner pipe surface. Normally the flow in heating pipes is turbulent (Re>2300).

RESULTS

Calculated necessary power consumptions for circulators needed for handling the peak space heating loads are presented in the table below.

The calculations, see Table 1, of the needed hydraulic power – the pump capacity – for circulating central heating water in single- and double-family houses confirm earlier evaluations, namely that in the vast majority of Danish single- and double-family houses this need is very small, compared to the power of the pumps used so far, namely less than 1 W. The combinations of parameters in Table 1, which require more than 1 W are quite rare. For calculating the electric power needed, pump efficiencies are assumed to be quite good, ranging from 5 – 30 % based on pump and system characteristics for small Biral MC10 (cooling of 30 K) and MC12 (cooling of 15 K) pumps. In the dominant cases, the necessary flow could be provided with a pump using less than 10 W electric power. Obviously the power need depends on the need for heating, that is, the size and the insulation standard of the house, as well as the design of the central heating system (as shown in the table). In few unfavourable cases the need could be larger than 10 W electric power.

Results of experimental tests

The calculations were confirmed in practice by experimental tests in 12 district heated one-family houses (mostly built in the 1970s), one house heated by an oil fired furnace, and 2 new houses with district heating, built according to the new, tightened building regulations. Since late in the year 2004, the existing circulators in these 15 houses have been replaced with a number of different brands and types of pumps, all with quite different capacities. The results of the experimental tests did not provide a large statistical material, but clearly show that the pumps with the lowest capacities have drawn a power of 5-10 W as anticipated (see Figure 2). The two new houses are number 14 and 15.

For houses in Denmark, power consumptions like before replacement in 1, 3 and 10 are most common, see Figure 2. Looking at the graph, however, it is obvious that most of the houses *in the test* have fairly low power consumptions before the replacements of pumps. This is not typical but due to the fact that this particular district heating supplier was conscious about saving electricity and had earlier advised its clients to adjust their traditional 3 step Grundfos UPS pumps to step 1 operation mode, which typically is plenty to distribute the heat. In some of these cases, (4, 5, 6, 7, and 9) replacing pumps at step 1 with so-called "1st generation energy saving pumps" have not at all reduced electricity consumption. The reason is that these 1st generation pumps, despite their automatic capacity control, have over-capacity even at their lowest level, and have no better efficiency than those they replaced. Such replacement makes no sense from an electricity saving point of view and should be avoided.

Table 1. Heating system pressure drop and necessary hydraulic and electric power as a function of heating demand, roughness of pipes, pipe length and cooling of heating system water.

Cooling [K]	30			15		
Heating demand [kW]	5	10	20	5	10	20
Flow [m^3/h]	0.143	0.287	0.573	0.287	0.573	1.147
Pipe condition / Pipe lenght	**Pressure drop Δp [kPa]**					
Smooth / 50	11.1	10.7	10.9	15.9	14.7	15.4
Rough / 50	13.9	12.9	13.4	28.2	24.3	26.2
Smooth / 100	13.2	12.4	12.8	22.9	20.5	21.9
Rough / 100	18.9	16.8	17.8	47.4	39.7	43.4
Pipe condition / Pipe lenght	**Hydraulic power P_h [W]**					
Smooth / 50	0.44	0.85	1.74	1.27	2.35	4.91
Rough / 50	0.55	1.03	2.13	2.25	3.87	8.35
Smooth / 100	0.53	0.99	2.04	1.82	3.26	6.96
Rough / 100	0.75	1.34	2.83	3.78	6.32	13.83
Pipe condition / Pipe lenght	**Electric power P_{el} [W]**					
Efficiency ($\eta_p \cdot \eta_{mo}$) [-]	0.05	0.10	0.15	0.10	0.20	0.30
Smooth / 50	8.8	8.5	11.6	12.7	11.7	16.4
Rough / 50	11.1	10.3	14.2	22.5	19.4	27.8
Smooth / 100	10.5	9.9	13.6	18.2	16.3	23.2
Rough / 100	15.0	13.4	18.9	37.8	31.6	46.1

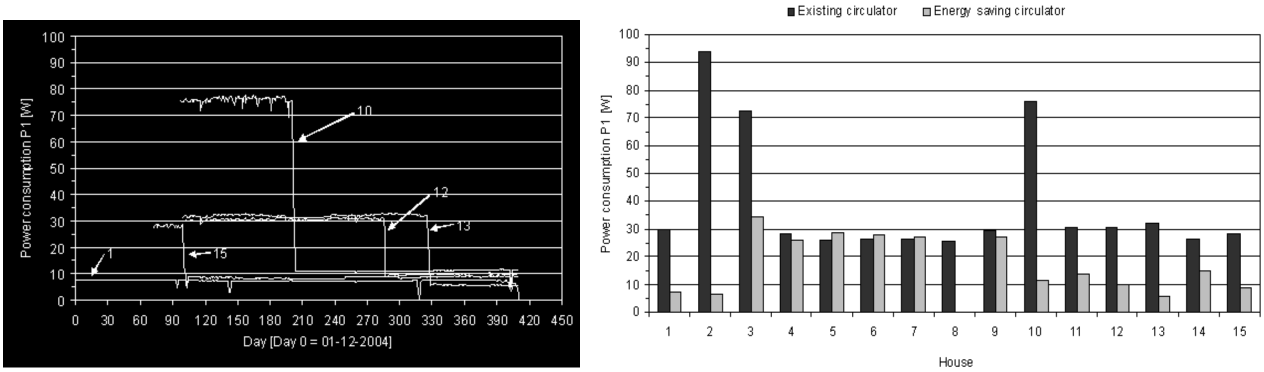

Figure 2. *Left: Measured power consumption development for circulators in selected house. Right: Measured average power consumption in all houses before and after replacement with energy saving circulators. (The electricity consumption in kWh per year at continuous operation is calculated by multiplying with a factor of 8.75).*

The practical test shows that the pumps with the lowest capacities, (1, 2, and 10-15) have: 1) reached the lowest power consumption and 2) also had sufficient capacity to provide the heat needed during the Danish winter climate of the test period. For some of the circulators the test period was a full heating season, while others have run for less than half a heating season. Electricity consumption for pumping in the houses with these small circulators points towards 45 – 90 kWh per year, a reduction of 30 – 85 % as compared to the old replaced pumps, which in the test essentially all were of the type Grundfos UPS xx-40, mostly put in lowest capacity, step 1, position.

Future needs for power for circulator pumps in Denmark and Europe

The total electricity consumption for circulation pumps in Danish single- and double-family houses is about 460 GWh per year. Small circulator pumps have an average service lifetime of about 13 years. There are approximately 970,000 Danish single- and double-family houses with need of a circulator. If supported by campaigns and subsidy schemes it is expected that in the long term all those pumps could be replaced by the most energy efficient and best adapted circulators with an average power consumption of 10 W. The electricity consumption for these 10 W pumps operated continuously the whole year amounts to about 90 kWh per year or about 90 GWh per year for the country as a whole. Total savings compared to present consumption equals about 370 GWh per year for Denmark.

It is estimated by the world leading pump manufacturer Grundfos that 120 millions of small circulation pumps are in operation in the EU countries and together they use approximately 60 TWh per year or 500 kWh per pump (Grundfos 2005). These circulators can be attributed about 15 % of the electricity consumption in a standard European household. Some 12 millions pumps are replaced each year. If all of these pumps sold in the future were the most energy efficient *and properly sized* pumps it is realistic to assume that the electricity consumption could be reduced to an average level of 10 W or 90 kWh per year as presumed in the above mentioned scenario for Denmark. Such a gradual replacement over 10 years will result in an annual lowering of electricity consumption in EU for this purpose of about 5 TWh/year. After a total replacement within these 10 years the electricity for the purpose will have fallen from the assumed 60 TWh today to around 10 TWh, i.e. a reduction in the electricity consumption of about 50 TWh per year. This is based on having the pumps running continuously all year, as is common in Denmark. In case of switching off the pumps during summer, etc., electricity consumption before and after, as well as the savings will be lower.

For EU the full electricity savings of 50 TWh per year after 10 years (or maybe 13 years) will result in the saving of 17 base-load power plants each with a capacity of 500 MW. Considering that the savings are in base load power, and that the whole effort to save electricity is mainly rooted in a wish to reduce CO_2 emissions, it seems fair to assume that the savings obtained will be utilized to cut down, not on e.g. wind power production, but rather on coal-fired power production. In that case annual CO_2 emissions in the EU would be reduced by about 50 millions tons CO_2 per year. This is more than 1 % of EU's total CO_2 emissions or about one sixth of the 8 % reduction that EU is committed to according to the Kyoto protocol. If oil- or gas-fired power plants are closed instead of coal-fired plants the reduction in CO_2 emissions would be 25 % and 44 % lower respectively. In a future based entirely on renewable energy the annual electricity savings of 50 TWh obtained by this relatively small change in user technology can in EU save the construction of about 10,000 large 2 MW wind turbines assuming a capacity factor of 0.25, i.e. an annual production of energy equal to 25 % full capacity over the year.

Recommendations for the future

In Denmark new energy regulations were implemented in 2006 requiring taking into account also the pumping power consumption. In this connection it is recommended to use the new small energy efficient pumps, and it should be highly considered to implement direct demands for maximum power consumption, in the same way as such requirement already exist for ventilation systems (Erhvervs- og Byggestyrelsen 2006). It is also recommended to focus on replacement of old pumps in relation to a new Danish scheme about inspection and improvement of boilers and heating systems older than 15 years, since such replacements could be carried out for a modest installation cost and typical simple pay back times of 4 -9 years. Various campaigns, including subsidies, should be run to ensure that all new installations as well as all replacements of circulators end up with small efficient pumps, sufficient for the task. This seems both environmentally sound and economically beneficial. It should be considered too, to accelerate replacement to this kind of pumps, possibly supported by requirements in the building codes.

Conclusions

The calculated need for hydraulic power to circulate water in central heating systems in one- or two-family houses is found to be less than 1 W. Even with a modest average efficiency of 10 % this corresponds to less than 10 W electric power. Comparison to the 40-60 W power consumption of the pumps used so far indicates a substantial potential for electricity savings. These calculations have in this project been confirmed through field experiments in houses in Denmark. A power consumption of 5-8 W has proved sufficient to provide satisfactory space heating in the winter climate during the test period.

Future need for electricity for circulation pumps in Denmark's small houses can be reduced by 400 GWh/year, or about 1 % of total electricity consumption, by replacing present pumps with the best, recently marketed pumps. If coal-fired power production is assumed to be saved, this would reduce CO_2-emission in Denmark with more than ½ %. For EU a similar scenario could save the construction and operation of 17 large power plants and 50 million tons of CO_2 emission per year.

The development of circulation pumps suggest a research strategy in the field of energy saving, guided not by efficiency of single component alone, but supplemented by analysis of the need for the service to be provided. Also, the historic development emphasizes the importance of maintaining research programs that are open and independent of immediate short term business interests.

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