Increasing the value of household appliances by adding a heat pump system

Peder Bengtsson

Faculty of Health, Science and Technology

Energy Technology

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VIPP VALUES CREATED IN FIBRE-BASED PROCESSES AND PRODUCTS

Inspired by Scandinavia

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Abstract

Historically, domestic tasks such as preparing food and washing and drying clothes and dishes were done by hand. In a modern home many of these chores are taken care of by machines such as washing machines, dishwashers and tumble dryers. When the first such machines came on the market customers were happy that they worked at all! Today, the costs of electricity and customers' environmental awareness are high, so features such as low electricity, water and detergent use strongly influence which household machine the customer will buy. One way to achieve lower electricity usage for the tumble dryer and the dishwasher is to add a heat pump system.

The function of a heat pump system is to extract heat from a lower temperature source (heat source) and reject it to a higher temperature sink (heat sink) at a higher temperature level. Heat pump systems have been used for a long time in refrigerators and freezers, and that industry has driven the development of small, high quality, low price heat pump components. The low price of good quality heat pump components, along with an increased willingness to pay extra for lower electricity usage and environmental impact, make it possible to introduce heat pump systems in other household products.

However, there is a high risk of failure with new features. A number of household manufacturers no longer exist because they introduced poorly implemented new features, which resulted in low quality and product performance. A manufacturer must predict whether the future value of a feature is high enough for the customer chain to pay for it. The challenge for the manufacturer is to develop and produce a high-performance heat pump feature in a household product with high quality, predict future willingness to pay for it, and launch it at the right moment in order to succeed.

Tumble dryers with heat pump systems have been on the market since 2000. Paper I reports on the development of a transient simulation model of a commercial heat pump tumble dryer. The measured and simulated results were compared with good similarity. The influence of the size of the compressor and the condenser was investigated using the validated simulation model. The results from the simulation model show that increasing the cylinder volume of the compressor by 50% decreases the drying time by 14% without using more electricity.

Paper II is a concept study of adding a heat pump system to a dishwasher in order to decrease the total electricity usage. The dishwasher, dishware and water are heated by the condenser, and the evaporator absorbs the heat from a water tank. The majority of the heat transfer to the evaporator occurs when ice is generated in the water tank. An experimental setup and a transient simulation model of a heat pump dishwasher were developed. The simulation results show a 24% reduction in electricity use compared to a conventional dishwasher heated with an electric element. The simulation model was based on an experimental setup that was not optimised. During the study it became apparent that it is possible to decrease electricity usage even more with the next experimental setup.

Sammanfattning

Historiskt så har alla hushållssysslor som diskning, tvättning och torkning av textilier gjorts för hand. I dagens moderna samhälle utförs det mesta av de sysslorna av disk, tvättmaskiner, torktumlare och torkskåp. När de första hushållsprodukter kom ut på marknaden var man glad att de överhuvudtaget fungerade. Idag har kraven på sådana produkter ökat betydligt i takt med ökade elpriser och ett större miljöengagemang hos slutkunderna. Ett sätt att minska vissa hushållsprodukters elförbrukning och därmed miljöpåverkan är att bygga in ett värmepumpssystem.

Funktionen hos ett värmepumpssystem är att hämta energi från en källa vid en lägre temperatur och avge energi till en källa vid en högre temperatur. I kylskåp och frysar har värmepumpssystem funnits länge vilket har drivit fram utvecklingen av högkvalitativa värmepumps komponenter till ett lågt pris. Tillgång till komponeter tillsammans med kundernas ökade efterfrågan på produkter med låg elförbrukning och låg miljöpåverkan ökar incitamentet att bygga in ett värmepumpssystem i fler hushållsprodukter.

Det är en stor risk att införa ny teknik till en produkt. Många tvättmaskinstillverkare i Sverige var tvungna att lägga ner tillverkningen på grund av bristande kvalitet och dåligt mottagande från kunderna av nya tekniska funktioner i tvättmaskinen. En tillverkare måste förutse om hela kundkedjan är bered att betala för värdet av en ny funktion i en produkt. För att lyckas är utmaningen för en tillverkare att förutspå den framtida viljan för kunderna att betala för en funktion och lansera den vid rätt tidpunkt med rätt kvalitet.

Värmepumpstorktumlare har funnits på marknaden sedan år 2000. I artikel I så utvecklades en dynamisk simuleringsmodell baserad på en värmepumpstorktumlare som finns på marknaden. Resultat mellan mätningar och simuleringar överensstämde bra. Med simuleringsmodellen undersöktes hur storleken på kondensorn och kompressorns cylindervolym påverkade hela värmepumpstumlaren. Resultaten från simuleringsmodellen visade att en ökning av kompressorns cylindervolym med 50% inte påverkade elförbrukningen men sänkte torktiden med 14%.

Artikel II är en konceptstudie som undersöker möjligheten att minska elförbrukningen från en diskmaskin genom att bygga in ett värmepumpssystem. Diskmaskinen med diskgods och vatten värms av kondensorn och en vattentank kyls av förångaren. Den största delen av energin

från vattentanken uppstår genom att vattnet fryser till is. En prototyp och en dynamisk simuleringsmodell utvecklades, byggdes och jämfördes mot varandra med god överenstämmelse. Simuleringsresultaten visade att elförbrukningen i en värmepumpsdiskmaskin var 24% mindre jämfört med en traditionell diskmaskin som värms med ett elelement. I studien upptäcktes möjligheter att göra förbättringar för en framtida prototyp för att ytterligare minska elförbrukningen.

Preface

This work was performed in cooperation with ASKO Appliances AB, which is a part of the Gorenje Group, one of Europe's largest household appliance manufacturers. The Gorenje Group is represented in more than 90 countries worldwide. ASKO is the global premium brand of the Gorenje Group.

I have been working at ASKO Appliances AB since 2000, specialising in stress analysis of washing machines and the performance of the tumble dryers. ASKO Appliances AB and Karlstad University have had cooperation since 2001. Our work together, with me as supervisor, has involved two PhD students, about twenty master theses, on drying process in a tumble dryer.

I began my PhD studies in Environmental and Energy systems in September 2011. The initial motive was that ASKO Appliances AB wants to study how to decrease the electricity usage of household products by adding a heat pump system. This thesis is written more from the perspective of a household product manufacturer rather than from an academic perspective. My wish is to use prototypes and simulations to show how heat pump systems can be used to decrease electricity usage in household products.

Acknowledgement

First I would like to thank ASKO Appliances AB and the multidisciplinary Industrial Graduate School VIPP - Values Created in Fibre Based Processes and Products - at Karlstad University, with financial support of the Knowledge Foundation, Sweden.

I want to thank all the personnel at ASKO Appliances AB for allowing me the space to perform my experimental work and their willingness to discuss different technical solutions.

Thanks to Professor Björn Palm and PhD Samer Sawalha at KTH, Royal Institute of Technology, for helping me and showing me how to perform simulations in energy systems.

I would also like to thank my supervisors, Associate Professor Jonas Berghel and Associate Professor Roger Renström.

List of Publications

This thesis is based on the following papers, referred to in the text by their Roman numerals.

Paper I Bengtsson, P.; Berghel, J.; Renström, R. Performance Study of a Closed-Type Heat Pump Tumble Dryer Using a Simulation Model and an Experimental Set-Up. Drying Technology, 2014, 32, 891–901.

Paper II Bengtsson, P.; Berghel, J.; Renström, R. A Houshold Dishwasher Heated by a Heat Pump System using an Energy Storage Unit with Water as the Heat Source. Submitted to International Journal of Refrigeration, June 2014.

Other related publications listed below are not included in this thesis.

Berghel, J.; Brunzell, L.; Bengtsson, P. Performance Analysis of a Tumble Dryer. Proceedings of the 14th International Drying Symposium, Sao Paulo Brazil 22–25 August 2004, Vol. B, pp. 821–827.

Brunzell, L.; Beiron, J.; Bengtsson, P. Temperature as an Indicator of Moisture Content and Drying Rate: A Control Strategy for an Air-Vented Tumble Dryer. Proceedings of the 15th International Drying Symposium, Budapest Hungary 20–23 August 2006, Vol. B, pp. 761–764.

The thesis author's contributions

Paper I — The planning, development and work with the experimental setup and the simulation model was performed by Peder Bengtsson. The writing was done jointly.

Paper II — The planning was done jointly. The development and work with the experimental setup and the simulation model was performed by Peder Bengtsson. The main part of writing was done by Peder Bengtsson.

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1. Introduction

Washing and drying clothes and dishes have been done by hand for a long time. However, in developed countries washing machines, dishwashers and tumble dryers have become increasingly common. In the past it was mostly the women who learned from their mothers how to wash clothes. Today, a lot of information about what temperature to use, for how long, which detergent and how much, mechanical agitation, how to clean spots, and which clothes could be washed together without becoming discoloured has been lost. Instead are most of this 'washing' knowledge is now built in to washing machines. Developing automatic features with built-in knowledge is one of the most important areas in the household appliance industry today.

ASKO Appliances AB is in its origin a Swedish company which has 60 years' experience in developing, manufacturing and selling dishwashers, washing machines and tumbler dryers. Their brands in Sweden are ASKO and CYLINDA, and in the rest of the world they sell under the ASKO brand. The first washing machine on the market from ASKO Appliances AB was built in 1950. It consisted of a container with a rotating drum into which clothes, water and detergent were put see Fig. 1.

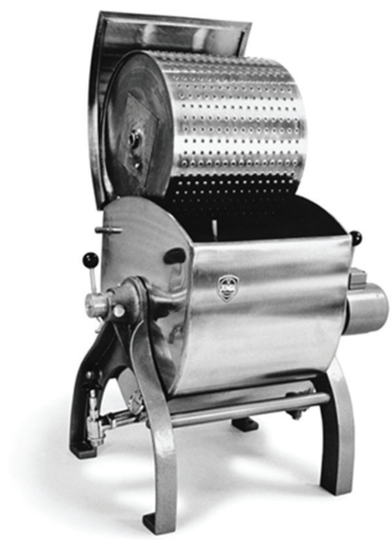

FIG. (1). The first ASKO washing machine, made in 1950. The name of the factory and the brand was in the beginning 'Junga verkstäder' [6] .

It was not what we today would call an 'automatic' washing machine. The clothes were, of course, rotated in the drum, but the user had to put in water and detergent, heat the water, decide on the washing temperature and choose how long the washing should continue. It was not until the 1960 and 1970s that the first automatic washing machines appeared on the market. ‘Automatic’ means that the machine takes care of the water use, temperature and washing time. In the late 1980s the first electronic washing machines arrived, which allowed the manufacturer to put more knowledge into the washing machine to help users wash their clothes.

FIG. (2). A modern fully electronic washing machine from ASKO Appliances AB with a lot built-in knowledge such as automatic programmes [6] .

A modern washing machine today is full of electronics with many automatic programs (Fig. 2).

A large part of electricity usage in our homes is a result of washing and drying clothes and washing dishes. When the price of electricity rises the focus on decreasing electricity usage in our home increases. Environmental consciousness also influences users to buy household equipment with low electricity usage. In this study, the use of heat pumps is investigated in order to decrease electricity usage for a tumble dryer and a dishwasher.

Adding a heat pump system to an appliance is always a cost for the manufacturer. The critical issue for the manufacturer is whether it is possible to get a matching or greater premium from the customer chain for the household product because of the added heat pump system. The risk is if the customer chain does not adopt and pay the extra premium for the added heat pump system, which will bring huge economic losses for the manufacturer. On the other hand, if the customer chain adopts and pays the extra premium for the added heat pump system it will bring a large economical profit for the manufacturer. This is a prerequisite for the introduction of an added heat pump system in a household appliance.

The aim of this thesis is to show how to increase the value of tumble dryers and dishwashers by adding a heat pump system. The increased value occurs from the reduced total electricity usage and environmental impact that the heat pump system will contribute when the appliance is used.

1.1. Electricity usage for household appliances

The electricity usage for household appliances around the world is a significant part of a country's total electricity usage. In the USA is it estimated that up to 3% of residential electricity is used in clothes dryers [1]. Others claim that 6% of world power consumption derives from inefficient household clothes tumble dryers [2]. In Sweden, approximately 1% of total household power is used for drying clothes [3].

How much electrical power household appliances use depends on many factors. Here are some examples of estimated electricity usage for household appliances in the literature. In Sweden the estimated energy use for an average household in 2001 [4] is shown in Fig. 3.

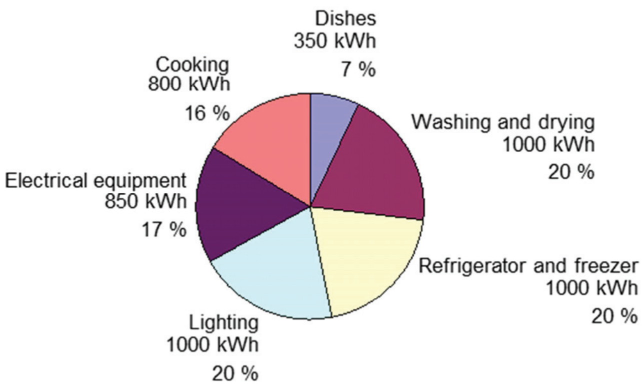

FIG. (3). Use of electricity, four persons in a household in Sweden 2001 [4].

The electricity usage for washing and drying was estimated to be 1000kWh per year and for dishes 350kWh per year [4]. Another study showed that on average in 2001, a dishwasher in a household consumes about 231kWh per year in Sweden [5]. The both studies gives an average annual electricity usage for dishwashers was estimated to be 290kWh [4,5]. For washing machines the estimated annual electricity usage per household for different countries in 2004 is shown in Figure 4 [5].

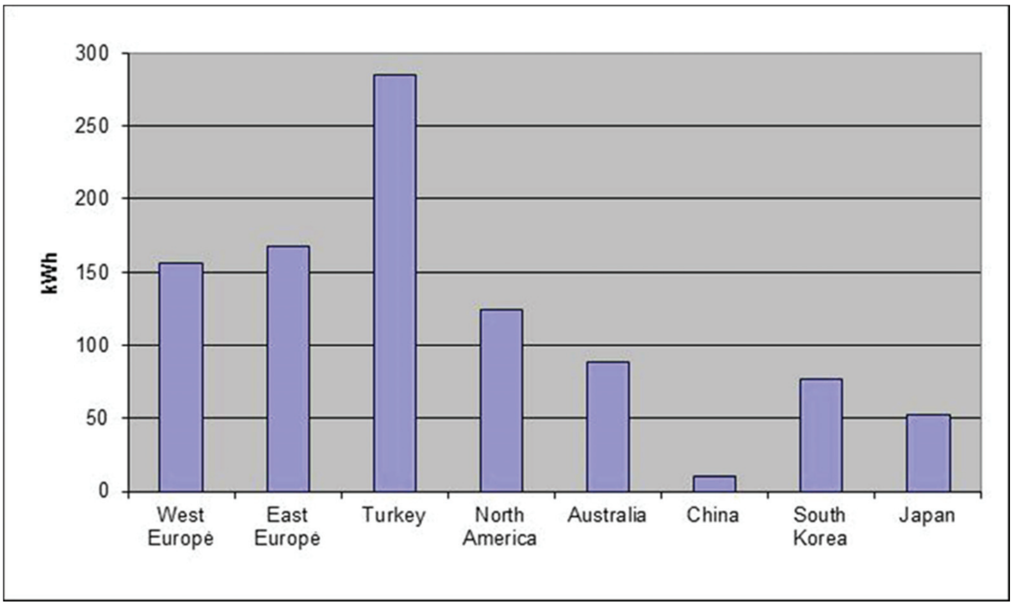

FIG. (4). Annual electricity use in 2004 for laundry washing per household in kWh [5].

In Western Europe the estimated electricity usage for laundry washing was 152kWh [5] in 2004. From the values from Figure 3 and 4 the electricity usage for drying can be estimated to be 1000 – 152 = 848kWh. That is a reasonable estimation considering that the electricity usage for an ordinary tumble dryer is 0.64kWh/kg textiles, and for a modern washing machine 0.19kWh/kg textiles.

Table (1). Estimated annual electricity usage for washing dishes, washing and drying clothes in a modern household in Sweden in the 2000s [4,5].

	Yearly electricity usage in a household in Sweden in the 2000s
Dishwasher	290 kWh
Washing machine	152 kWh
Tumble dryer	848 kWh

1.2. Development of the specific electricity usage for dishwashers, washing machines and tumble dryers

The four factors that affect the washing results of the textiles (in a washing machine) and dishware (in a dishwasher) are chemical action, mechanical action, temperature and time during the washing operations. By combining the four factors it is possible to reach the same 'clean' results with reduced electricity usage. A manufacturer can choose to use the factors in order to reduce the electricity usage. Tables 2 and 3 illustrate the development of electricity usage between an old and a modern dishwasher and washing machine from ASKO Appliances AB.

Table (2). Development of electricity usage for ASKO Appliances AB washing machines [6,7].

	Year 1977	Year 2003	Year 2014
Water usage	55 liters/kg textiles	9.8 liters/kg textiles	9.8 liters/kg textiles
Electricity usage	1.06 kWh/kg textiles	0.19 kWh/kg textiles	0.18 kWh/kg textiles
Total operating time	115 min	125 min	200 min

Table (3). Development of electricity usage for ASKO Appliances AB dishwashers [6,7].

	Year 1977	Year 2003	Year 2014
Water usage	60 liters/cycle	9.9 liters/cycle	9.9 liters/cycle
Electricity usage	3.7 kWh/cycle	1.1 kWh/cycle	0.82 kWh/cycle
Total operating time	105 min	160 min	200 min

For washing machines and dishwashers there is a reduction in water use, which leads to lower electricity usage. However, the duration of washing is increased to compensate. In the last ten years the decrease in electricity usage has flattened out because it is difficult to reduce water use any further.

Historically, there has not been any significant reduction in electricity usage for the two traditional types of tumble dryers, vented and condenser [7]. The only major improvement in electricity usage (compared to dishwashers and washing machines) was when heat pump technology was introduced in a closed cycle dryer (Table 4).

Table (4). Development of electricity usage for ASKO Appliances AB tumble dryers [6,7].

	Year 1985	Year 2014
Vented tumble dryer	0.67 kWh/kg textiles	0.59 kWh/kg textiles
Condense tumble dryer	0.73 kWh/kg textiles	0.64 kWh/kg textiles
Heat pump tumble dryer		0.24 kWh/kg textiles

The motivation for manufacturers in Europe to develop dishwashers, washing machines and tumble dryers with low electricity usage was increased when the EU-energy labelling system appeared in the 1990s. The label system forced manufacturers to measure the electricity usage in a standardized manner and put the electricity usage value on the front of the machine in the store. This made it possible for end consumer in the store to compare the electricity usage of different machines and thus resulted in competition between manufacturers to have the machine with the lowest electricity usage.

New techniques are often new for a short time before they become the state-of-the- art technical solution. So manufacturers are very secretive about important technology, especially if it is new. This could be the reason why so little is reported in the open literature. The most knowledgeable core is at the manufacturers. It is obvious that new technology is required to reduce electricity usage in the future. Many articles are available about optimizing the electricity usage of existing tumble dryers, but none describe new technology. However, a few research reports have been published regarding new technology in dishwashers and washing machines that can reduce electricity usage.

De Paepe et al. [8] suggested using the heat from the wastewater of the dishwasher to heat the fresh water entering the dishwasher. Calculations and performance tests showed a 25% decrease in total electricity usage. Hauer et al. [9] used an additional absorption cycle during the drying stage in a dishwasher; the total electricity usage decreased by 25% compared to a conventional dishwasher. Persson [10] heated a dishwasher and a washing machine using a hot water circulation loop, transferring the heat using a heat exchanger. Experimental results showed that it is possible to replace up to 90% of the electricity usage. Just changing the energy source from electricity to hot water does not give any reduction in energy usage. Another way to decrease the electricity usage is to add a heat pump system to the dishwasher.

1.3. Heat pump system

Refrigeration engineering mainly started to develop in the early 1900s, although the basis in thermodynamics was established somewhat earlier [11]. In the beginning, refrigeration/heat pump systems were used to cool food. Today, a large part of the refrigeration/heat pump system is used to create a good indoor climate. In developed countries 15-20% of all electricity is used for driving refrigeration/heat pump equipment.

The purpose of a heat pump is to extract heat Q_{evap} from a lower temperature source (heat source) and release heat Q_{cond} to a higher temperature sink (heat sink), see Fig. 5. The only difference between a refrigeration system and a heat pump system is that a refrigeration system extracts the useful heat at the evaporator while a heat pump system rejects the useful heat at the condenser.

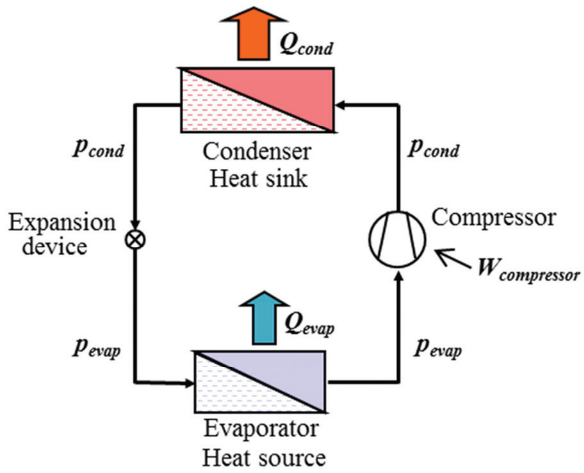

FIG. (5). Schematic of the components and function of a heat pump system

The basic configuration of a heat pump/refrigeration system includes evaporator, condenser, compressor, expansion device and the refrigerant which circulates in the closed loop formed by the components, which are connected by tubes. When the compressor $W_{compressor}$ is running, the system will end up with two pressure levels. The high pressure p_{cond} is in the condenser and the low pressure p_{evap} is in the evaporator. The characteristics of the refrigerant cause it to condense in the condenser and evaporate in the evaporator. During evaporation to gas at the lower pressure, the refrigerant absorbs heat, corresponding to the latent heat of evaporation. During the process at the higher pressure side, the refrigerant releases heat and condense back to liquid.

1.3.1. Refrigerants

One important component in a heat pump/refrigeration system is the refrigerant. There are many alternatives, all of which have different characteristics and have to satisfy a number of requirements, which can be divided into five groups [12,13]:

- **Chemical**: Stable and inert
- **Health and Safety**: Nontoxic, non-flammable
- **Environmental**: No Ozone Depletion Potential (ODP), minimal Global Warming Potential (GWP)
- **Thermophysical properties**: Critical point and boiling point temperature appropriate for application, moderate liquid molar heat capacity, low liquid viscosity, high liquid thermal conductivity.
- **Miscellaneous**: Soluble with lubricants, high vapour dielectric strength, low freezing point, compatible with common materials, easy leak detection, low cost, readily available.

It is difficult to find a refrigerant that fulfils all of these requirements in each case. The choice of refrigerant is individual and always a compromise.

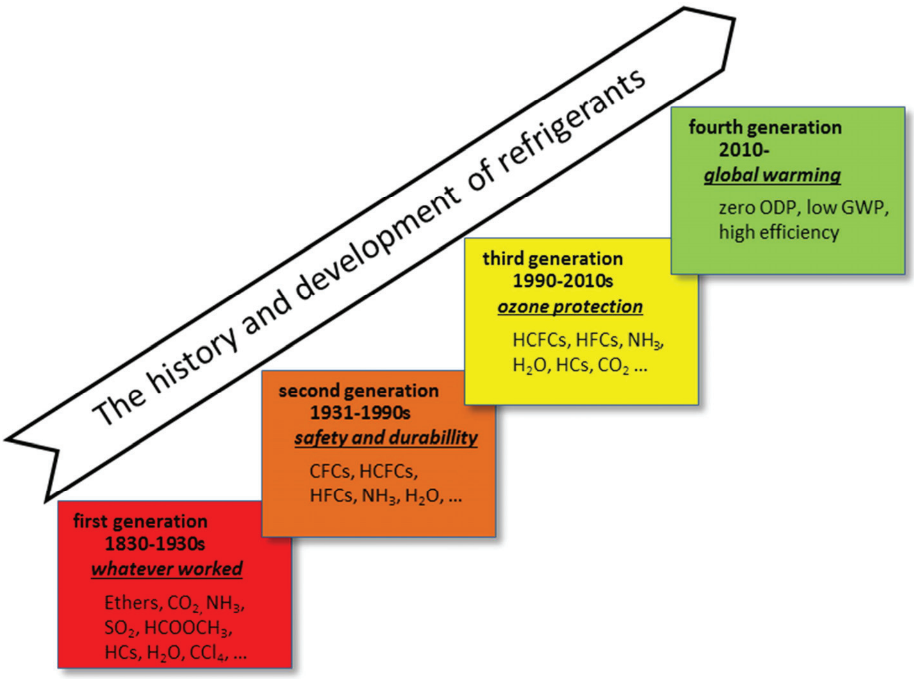

FIG. (6). The progression of refrigerants over four generations [13].

The choice and requirements of refrigerants has varied over time. Figure 6 depicts the progression of refrigerants from their advent through four generations.

First generation, whatever works: The main purpose was to cool down food and so forth, using whatever worked. Natural refrigerants such as carbon dioxide, ammonia and propane dominated.

Second generation, safety and durability: The many serious toxic and explosive accidents that occurred pushed the industry to develop safe refrigerants. The new chlorofluorocarbon (CFC) was introduced as a nontoxic and non-flammable solution.

Third generation, ozone protection: Research reports in the late 1970s pointed out that the chloro from CFC was reacting with ozone in the atmosphere. New synthetic refrigerants such as hydrofluorocarbons (HFC) without chloro were developed and introduced on the market.

Fourth generation, global warming: Warnings about global warming appeared during the 1980s and 1990s. Some refrigerants, for instance HFC, have a large GWP. So the fourth generation focuses on using refrigerants with low GWP value.

The fourth generation is just beginning in the 2010s. It is difficult to predict which refrigerants will dominate in the future. However, taxes and regulations force the selection of refrigerants. A new tax was introduced in 2010 in the Nordic countries that affect the phase out of HFC refrigerants. For instance, from 2010 the tax for R134a is 20Euro/kg in Denmark, 34Euro/kg in Norway and 28Euro/kg in Sweden [12]. A new regulation introduced in 2006 forbids refrigerants with GWP > 150 in Europe in new car models from 2011, and in all new cars from 2017 [14].

A large part of research, in the heat pump area today, is devoted to investigating and comparing new (with low GWP) and old refrigerants and the consequence of changing to the new refrigerants in different applications. Meanwhile, chemical industries are spending large amounts to invent new synthetic low GWP refrigerants in order to survive in the future.

1.3.2. Simulation

Both the tumble dryer and the dishwasher cycles are dynamic. A simulation of such a complete dynamic heat pump system includes several complex mathematical relationships. In this case it is an advantage to use computer programmes to evaluate heat pump systems. There are many examples in the literature.

Braun et al. [15] analysed two alternative drying systems, an air heat pump (reversed Brayton) tumble drying process, and a conventional closed cycle condenser tumble dryer. The simulation model was developed in Engineering Equation Solver (EES). Results from the simulation model show that the energy use of an air heat pump (reversed Brayton) tumble drying process is up to 40% lower than the conventional closed cycle condenser tumble dryer.

Using a simulation model, Novak et al. [16] compared the refrigerants R134a, R290 and R774 in a heat pump tumble dryer. They also converted two heat pump tumble dryers (originally R134a) to R290 and R774 and conducted experiments to compare the experimental and the simulation results. The result was that R290 has the lowest total equivalent warming impact factor. The transcritical CO_2 cycle and the subcritical R134a cycle in a heat pump tumble dryer were compared by Mancini et al. [17] using a steady-state simulation model. The model is based on fixed temperature approach values for the heat exchanger. The simulation results were applied to a transcritical CO_2 experimental setup. Experimental results showed a 9% reduction in electricity use for the CO_2 cycle compared to the R134a cycle.

Pal and Khan [18] developed a simulation model and proposed calculation steps for the design of different components of a heat pump dryer during the constant drying rate period. The model consists of three submodels: a drying model, a heat pump model and a performance model. Heat and mass balance between the refrigerant and the air circuits in the components is used to obtain a complete simulation model. A performance analysis using simulation models of five heat pump dryer configurations was performed by Saensabai and Prasertsan [19]. The models work under steady-state conditions, and the purpose of the analysis was to find the best configuration with the lowest energy use in different ambient temperatures and humidity profiles. Sarkar et al. [20,21] developed a simulation model of a transcritical CO_2 closed cycle heat pump dryer and validated it against experimental results. The model operates under steady-state conditions and has been used to predict the characteristic performance Coefficient Of Performance COP and Specific Moisture Extraction Rate SMER of a heat pump dryer with different bypass ratios for the drying air in the evaporator. Wang et al. [22] developed a simulation model in EES of two high-temperature heat pump systems. A performance analysis and comparison between the systems was made. The results from the model were used to design and build a prototype. EES has also been used for simulations of heat pump systems in other papers [23-27].

EES is commonly used to simulate heat pump systems. The program was developed by two professors, Dr William Beckman and Dr Sanford Klein, both of the University of Wisconsin [28]. Their experience in teaching mechanical engineering thermodynamics and heat transfer showed that students were spending too much time looking up property information and solving equations for their homework problems, tasks that did not help the students master the main subject material. Interesting practical problems could not be assigned because of their mathematical complexity. Dr Beckman and Dr Klein designed EES to allow users to concentrate more on design by freeing them from mundane chores.

Nowadays EES is one of the dominant programs for simulating heat pump systems and has been used in this thesis.

1.3.3. Evaluation of heat pump systems

There are different approaches to graduate efficiency and how environmentally friendly a heat pump system is [8,12,16,19-21,29-31]. The most used in the literature are the electricity usage [kWh] and COP [-]. Two other approaches are to use TEWI [kg CO_2 eq.] or LCI [MJ/unit].

Electricity usage. It is very common to rate and compare heat pump systems against each other, or to similar products without heat pumps. Here are some examples of theoretical and experimental research works based on electricity usage.

MB et al. [29] performed tests that showed that a well-designed engine-driven heat pump dryer could achieve a reduction of 30-50% in drying electricity usage. Saensabai and Prasertsan [19] analysed computer models of five heat pump dryer configurations, wherein steady-state models were run to find the best configuration with the lowest electricity usage in different climates with different ambient temperatures and humidity. Braun et al. [15] performed a parametric study and evaluated electricity usage.

Coefficient of performance (COP). The COP is also used as a performance value for heat pumps and refrigeration systems. For a refrigeration system, COP_{evap} is used and defined as the ratio of the useful refrigeration effect to the necessary operating energy. For a heat pump system, COP_{cond} is used and defined as a ratio of the useful rejected heat effect to the necessary operating energy.

Sarkar et al. [20,21] developed and validated a mathematical model of a transcritical CO_2 closed cycle heat pump dryer. The heat pump model was operated at steady-state condition and was used to predict the characteristic performance COP with different bypass ratios of air in the evaporator. De Paepe et al. [8] has also used COP when studied a transcritical CO_2 cycle and a subcritical R134a cycle in closed cycle heat pump tumble dryers.

Total equivalent warming impact (TEWI). The choice of refrigerant in a heat pump system is important and part of the total environmental impact. Different refrigerants affect the environment differently. In the past, some refrigerants decreased the ozone in the stratosphere, but they are forbidden today. The environmental impact of modern refrigerants is the global warming potential (GWP). Today it is more common to pay attention to both the refrigerant and the electricity usage when comparing and rating the environmental impact of a product by using the TEWI [12,16,30]. It takes into account both the direct effect related to refrigerant leakage to the atmosphere and the indirect part effect related to the electricity usage of the appliance.

For plug-in appliances, using hermetic compressors, the leakage rate is small and the refrigerant charge is also small. Thus the indirect effect dominates the calculation, representing up to 95% of the total contribution [16] with constant emission from electricity generation. For large installations and mobile air conditioning the direct effect of refrigerant leakage represents a larger contribution. The emission together with electricity generation is strongly dependent on the technology used to produce electricity: higher for coal, oil and gas, lower for hydroelectric, nuclear, wind and solar.

Total life cycle energy inventory (LCI). LCI is quantifying cumulative energy inputs and outputs for all life cycle stages. It calculates the total electricity usage for the raw material processing, the manufacturing and the use of the product.

Adding a heat pump system also adds a quantity of material. The compressor and the heat exchangers is a big part of a dishwasher total weight and consist of steel, aluminium and copper, which create an environmental impact during manufacturing and mining. The use of the product, the materials and the manufacturing jointly affect the total life cycle inventory. However, Boustani et al. [31] in the US concluded that 88 to 95% of the LCI arises from the use by the end consumer of washing machines, refrigerators and dishwashers. Thus the most effective way to reduce total LCI is to focus of how the end consumer uses the product. The end consumer's behaviour and use of the washing machine, tumble dryer or dishwasher affects the LCI as much or more than technical improvements of the products.

Today there are many actors on the market who influence the end consumer buying decisions and use. To really reduce environmental impact, the use of the product, the energy use, TEWI and all of these aspects should be considered. It is obvious that the companies who manufacture and sell products including heat pump systems have a vested interest in high ratings for their own products. They do not care which method or rating system is used. It is important to have something to show the end consumer that their product is one of the best on the market, whether 'best' means lowest electricity usage, highest COP value, lowest environmental impact or some other metric.

1.4. Objectives

The objective is to point out possible examples and improvements in implementing added heat pump systems in household appliances.

- For heat pump tumble dryers (which are common on the market today), the objective is to analyse and show the possibility of decreasing electricity usage and drying time by experiments and simulations.
- There is only one heat pump dishwasher on the market today, and very little experience of its function and performance. The objective is to show the potential of decreasing the electricity usage for a dishwasher with an added heat pump system.
- An added heat pump system increases the price of a household appliance. An objective is to illustrate how the decreased electricity usage and environmental impact increases the value of the household appliance using an added heat pump system. The increased value lies in increasing the willingness of the end consumer to pay a premium for it. If the willingness to pay more is higher than the cost for the added heat pump system, the manufacturer will be prepared to start the development and production of the product.

2. Development of products and features in the household appliance industry

To take a decision to develop, manufacture, promote, and sell a new feature like the added heat pump system is a big risk for a manufacturer. A decision to start or not start a project is based on past experiences in the industry, today's industry knowledge and an economical calculation.

2.1. Eighteen washing machine manufacturers disappeared from Sweden. What happened?

In the 1960s there were eighteen washing machine manufacturers in Sweden. All of them wanted to develop, manufacture and sell washing machines in the future as long as it was profitable. They included Electrolux, Electro Helios, Cylinda, Husqvarna, Värmos, Osby, Sellbergs, Crescent, CTC etc [7,32]. The last manufacturer was ASKO Appliances AB, which moved development and manufacturing to Slovenia in 2013. Some of these companies are still brand names in Sweden, but the machines are manufactured in other countries. Today the household appliance industry is global, and the big players have manufacturing units in countries with low costs and can fairly easy move manufacturing units.

The final reason for the most of the closures of washing machine manufacturers was low profitability, which resulted in closure, bankruptcy or acquisition by other companies. There were four reasons for their economic situation [7,32].

- **Investment in technical features that were wrong, or launched too early or too late.** Some manufacturers invested in technical features that were not well received by customers, which resulted in low sales volumes. Others launched good technical features, but did so too early, when the market was not yet ready.
- **Poor product quality.** Poor product quality with machines breaking down or underperforming led to dissatisfied customers and large after-sales costs. The bad product quality was due to complex technical solutions and poor knowledge of mass production.
- **Small or no sales network.** Small local manufacturers with small local sales organisations found it difficult to increase sales volume by expanding the market.
- **No in-house research and development, copying competitor's technology.** It is difficult for small companies to have their own

development organisation. This is acceptable when the technology is basic. However, as the speed of technical change increased, it was hard for many companies to develop a modern washing machine. Some copied a competitor design in every detail, indicating a lack of development organisation. It is a common belief that by copying one can only get 90% of the product's characteristics and performance [7]. In many cases this turned out to be the true. The copied products always had inferior performance and quality compared to the original.

Generally it was a combination of these reasons that led to low profitability.

The manufacturers' ability to survive was rigorously tested when the whole washing machine industry made technological leaps. They needed to adopt these new technologies if they wished to continue with the manufacturing of washing machine. There were three main areas in which manufacturers had problems keeping up with technology development [7,32].

1. **Heating the water in the washing machine with an electrical element**. In the first washing machines, users had to add the hot water themselves; it was not possible to heat the water in the machine. Introducing an electrical element into the machine to heat the water was a challenge for manufacturers who had a history of only mechanical manufacturing. A combination of wrong technical solutions, lack of development competence, and quality problems meant that some companies ceased to exist.
2. **Washing and centrifugation in the same machine**. There was no integrated centrifugation in old washing machines. To spin the washing, you had to have a separate centrifugation machine. Integrating centrifugation required that the mechanical structure be totally redesigned. This huge technological leap generates large vibrations and requires a high-speed electrical drive system. Manufacturers came up with different technical solutions for the drive system and for handling the vibration. Some solutions were not good enough and resulted in poor function and product quality. This technological leap was difficult for manufacturers without a well-functioning research and development department.
3. **Fully automatic machine with automatic wash programs**. Automatic wash programs mean that the user only needs to start the machine, and then the washing machine will automatically handle all the washing steps such as prewash, wash, rinse, and centrifugation. Developing and manufacturing the first electromechanical generation of

automatic washers required electrical competence. Developing and manufacturing the second generation of fully electronic machines required electronic competence. At first, fully electronic washers were of poor quality with large costs for the manufacturers. Automatic wash programs generated a new field of knowledge in research and development. With these automatic programs, it was possible to design and optimize wash and rinse performance while also keeping electricity and water use as low as possible. Today this is one of the core businesses of washing machine manufacturers. Many resources are invested in research and development in this area.

A similar evolution has occurred for other household products such as dishwashers and tumble dryers. For both was the introduction of fully automatic machine with automatic wash and dry programs big technical leaps. Other technical leaps for the tumble dryer were when the condenser tumble dryer and the heat pump tumble dryer appeared on the market. For dishwashers, other technical leaps are less obvious; the development progress occurred in small steps.

Today the household appliance industry is one of the most competitive in industry. The pace of development has increased. The lifetime for a design is shorter. Customers call for more features. Price competition is tough. Today, as in the past, there is no margin for a manufacturer to invest in large projects with wrong features. New technological leaps will continue. Manufactures face similar challenges, opportunities, and risks as they have in the past.

2.2. Types of customers for household appliances

All the manufacturers sell household appliances with the goal of making a profit. In order to be able to do so, it is very important to identify the customers and understand what their requirements are. There is more than one type of customer to consider when selling products. Manufacturers have identified the following four customer types: the end consumer, the consumer institute and magazine, the distribution system, and stores selling household appliances.

End consumer. The first obvious customer is, of course, the end consumer who uses and pays for the product. The product has to meet the end consumers' requirements and convince them that this is the best product for the service *'washing clothes or dishes'*. It is hard to define a typical end consumer, although manufacturers spend a lot of time of trying to understand how they act when deciding which product to buy. Consumer behaviour and requirements are totally different in different countries around the world.

Consumer institutes and magazines as *Råd och Rön* and *Choice*. This type of customer must be satisfied that the product will turn out well in their tests. Some end consumers read test reports on appliances in magazines before making a purchase, and manufacturers use test results for advertising, if they turned out well. Thus, manufacturers work hard to ensure that they get a good rating from the consumer institutes. Assessment criteria such as electrical usage, usability and noise levels are considered in some institute tests.

The distributors, the retail chain and the stores for household appliances. The entire distribution chain from wholesalers to stores consists of customers who have to be motivated to sell the manufacturers' products. The wholesalers and stores want to make money without having trouble with broken products of poor quality. If a store earns more money by selling a particular brand, or an employee gets some personal benefit, they will, of course, show the product and try to convince the end consumer to buy it. In order to sell many products at a good profit, wholesalers and stores need be treated well so that they are motivated to convince the end consumer to choose household products from that manufacturer.

Stammer et al. [33] surveyed how different types of end consumers act and look for products in different segments and prices for washing machines. They identified five types namely: 'brand-conscious buyers' (who have high quality expectations and are reluctant to search for low price), 'discount buyers' (who aim at simplifying the choice process, targeting discount shops), 'optimizers' (who are prepared to invest time and effort for price rewards), 'high-price shoppers' (with high quality and brand preferences, for which price has an important signalling role) and 'price seekers' (who consider price as the prominent decision criterion).

Features can provide great value for one group of customers and no value for another group. The whole customer chain behaves differently depending on which consumer group the machines are intended for. Here are some examples of surveys conducted in order to understand how different types of consumers react to different features and their willingness to pay for them.

Ward et al. [34] conducted a survey in the United States and found willingness to pay an extra $250–$350 for a refrigerator that has been awarded an ENERGY STAR label. The results provided evidence that respondents' willingness to pay was motivated by both private (energy cost savings) and public (environmental) benefits.

Willingness to pay for product brands was examined in the United States for products in different categories [35]. The conclusion was that consumers have a stronger preference and higher willingness to pay for brand name products for products with longer usage, such as electronics products rather than for clothes and food with a short life.

Galarraga et al. [36] investigated the willingness of consumers in Spain to pay extra for a dishwasher with a lower electricity usage. They observed sales of 318 dishwashers of different brands in different stores. It was found that 15.6% of the final price was actually paid for a reduction in electricity usage, reflected in the change from an (A) to (A^+) on the dishwasher energy label.

In the United States the value of the Green Power Partnership (which means that the manufacturer used green power for production) was examined [37]. The conclusion was that consumers would be willing to pay a $53 to $68 premium for a refrigerator produced by a Green Power Partner.

Ha et al. [38] undertook a survey in South Korea of the behavioural intention to purchase energy-efficient products such as air conditioners, TVs, fridges and washing machines. They concluded that existing beliefs about the positive impact of buying an energy-efficient product might persuade green consumers to select that option instead of an alternative with a lower price. The strength of these beliefs increased when energy-saving products were marketed as being innovative as well as energy-efficient.

Harris et al. [39] conducted a survey in New Zealand and Australia to determine whether sustainability is a selling point for dishwasher products. One conclusion was that there is growing consumer concern about the implications of global warming and the currently unsustainable level of exploitation of the earth's finite resources. This drives increasing consumer support for 'environmentally friendly' products and practices, and an increased willingness to pay for it.

2.3. When should a household manufacturer invest in new product features?

To understand and define a product feature, Kano et al. [40] present a model which evaluates patterns of quality of the feature, based on customer satisfaction with specific quality attributes and their degree of sufficiency. The Kano theory explains the relationship between the degree of sufficiency and customer satisfaction with a quality attribute. Witell and Löfgren [41] have used the theory, and compared it to other theories.

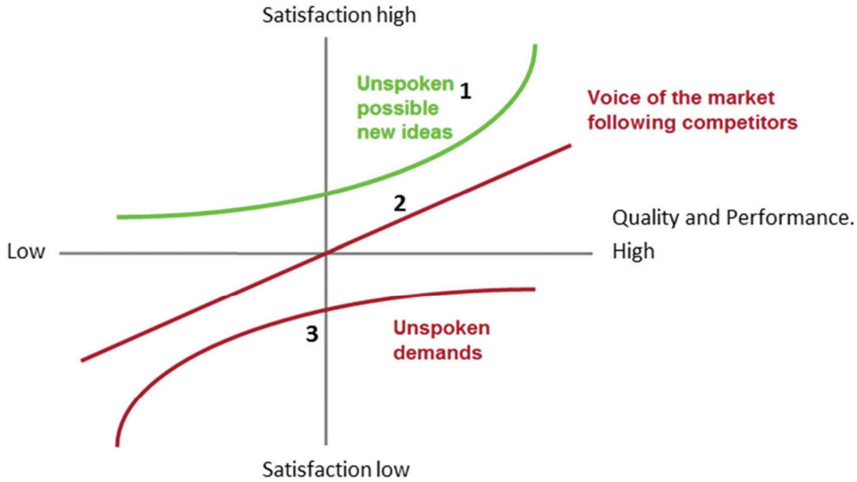

FIG. (7). The Kano diagram and ASKO Appliances AB's selected value groups for a modern washing machine.

By working with the Kano diagram, it is possible to understand and focus on developing the right features. Figure 7 shows an example of features for washing machines today in different groups. Three groups of features have been classified depending on whether, and how much, the end consumer is willing to pay for a feature in a modern washing machine.

Group 1: Features customers want, and pay much extra for. New innovative features which give extra value to the whole customer chain.

Special washing programs such as Quick, Jeans, etc.
High maximum washing load.
Attractive design.
Special drum surface to protect textiles.
Quickly wash the clothes clean.

Group 2: Features customers want, and pay extra for. Features which the technical brand leaders have.

Silent operation.
Easy to understand and use.
Low electricity and water use.

Group 3: Features customers require and will not pay extra for. Features all the comparable brands have.

Automatic washing program.
High maximum spin speed (rpm.)
No vibration on the floor.
Wash the clothes clean.

The examples in the three groups are time-dependent and have varied over time. They would have been totally different for the 1980s and 1990s compared to today. Sometimes changes occurred very quickly. Features in group one could be in group three in just a few years and vice versa, as shown below for high *maximum spin speed (rpm)*, *washing the clothes clean,* and *high maximum washing load.*

In the first machine (Fig. 1) the spin speed and the cleaning results were in group one. In the 1970s the cleaning result become a natural feature and was moving to group two. Finally in the 1980s customers would take it for granted. Not until the 2000s, did new features appear in group one: special automatic programs for specific textiles and a program to wash the clothes clean quickly. In the 1960s the ability to spin washing was a feature in group one. Users appreciated it because the clothes dried much faster after being spun in the washing machine. In the 1980s and up to the 2000s, manufacturers competed to have the machine with the highest spin speed. In the late 2000s this changed as the market became convinced that it a spin speed around 1400–1600rpm was sufficient. All the manufacturers already had machines at that spin level, and so this feature rapidly moved from group one to group three.

Historically the focus on the maximum washing load was quite high and this feature was in group two. From the 1980s until 2000s (when the focus was on spin speed) this was of less interest and so the maximum washing load moved to group three. Today the maximum washing load has become one of the most important values for a washing machine, and is in some cases used to rate different washing machines against each other.

A new feature always involves investigation of any new aspects regarding the feature. For example, does it affect any new legal requirements? Is it possible to get any new benefits such as eco labels like the 'Swedish Svanen'?

One disadvantage of this type of Kano diagram is that it merely reflects the situation at an instant in time. The values can change strongly over time, and household appliance industries are mostly interested in the value of a feature about one to five years in the future.

Abel [42] claimed that the timing of market entry for an feature is one of the most critical decisions manufacturers have to make. Hidding et al. [43] found that it generally best to enter the market closer to the inflection point in the S-curve where market growth increases rapidly. As previously mentioned, some washing manufacturers disappeared from the market because of bad economics caused by launching new features too early or too late. In papers discussing the benefits of when to introduce new technical features on the market [42-49] it common to create three groups [47,48,50]:

The first-mover advantage. First on market with a new technical solution, the pioneer. By starting earliest, first movers have more time than later entrants to accumulate and master technical knowledge [44]. However, information on how the market reacts is unknown in the beginning. Early stage quality problems can occur, and it is more difficult to lead than to follow [49]. A strong research and development department and a deep pocket (large-scale marketing for a long time) are keys to success as a first mover. In the business world being a first mover is usually associated with innovation and good performance [48].

The second-mover (early follower) advantage. In many situations it may not make a lot of sense to try to be the first mover. In environments where a first-mover advantage is likely to occur after years of losses, and then be short-lived, it could be better to wait until the market is ready. The second mover is able to use much technical and marketing information from the first mover.

The follower advantage. Followers have several advantages. They can focus merely on explaining why their products are better, while early entrants must first explain what their new feature or product is and does [43]. They have a lot of information and can avoid some early quality problems. However, they have missed the experience of years on the market (learning-by-doing) [42].

For some manufacturers the first-mover advantage is large and for others the follower advantage is large. However, the odds of succeeding with a new feature depend on how well you understand the market and the technology in order to time the introduction. All manufacturers have to decide whether it is better to move first, or second; to innovate or to imitate [47].

The willingness of the customer chain to pay extra for a feature depends on many conditions and changes over time. Figure 8 shows two examples illustrating the total cost to introduce the feature as extra material, developing costs, promotion, and the total extra premium for the feature. To be profitable a manufacturer needs the extra premium to be higher than the cost. The household appliance industry is always trying to predict the future of these two curves, which look different for each manufacturer depending on their unique situation, for example sales volume, promotion activities and extra material costs. Depending on whether the manufacturer chooses to be a first mover or a follower, they will decide to introduce the feature at different times. It will always be easier to analyse and define the curve afterwards and reflect on the results, but the household appliance industry will always have to do the opposite. To predict the shape of these two curves requires a lot of industry experience and know-how.

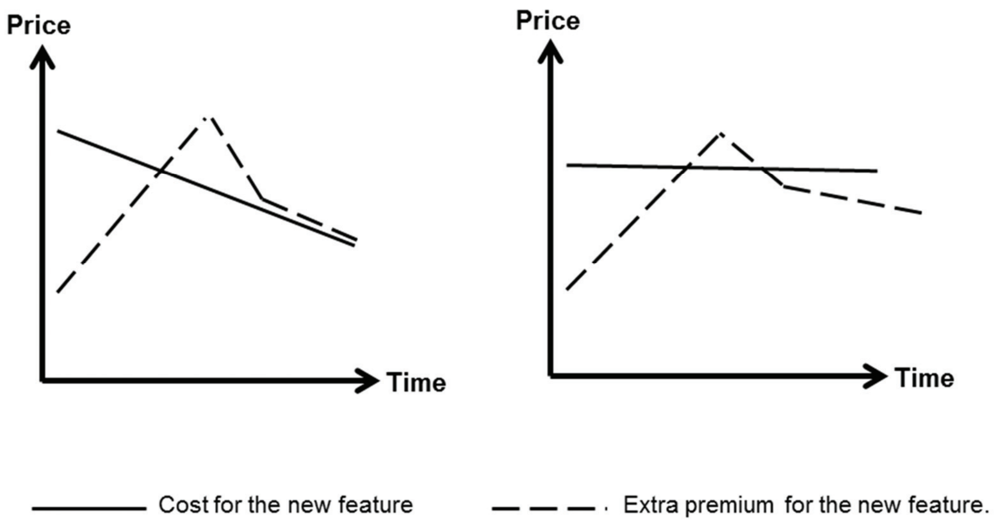

FIG. (8). The total cost and total extra premium for a feature changes over time for two examples of different type of features.

Traditionally the development and purchasing organisations are responsible for developing and predicting the cost (solid curve in Fig. 8) for a new feature when it is implemented in the product. Based on experience of earlier similar projects, the prediction is usually good. The curve predicting the extra premium for a feature (dashed curve in Fig. 8) is generally drawn by the sales and marketing organisations. This curve is much more difficult to draw and many factors affect its shape. To produce it, manufacturers have to understand how the whole customer chain (end consumer, consumer magazines, wholesalers and stores) will react to the new feature. How much money are the end consumers willing to pay extra? How will the magazines judge the feature? Will the wholesalers and the stores promote the new feature instead of others?

The diagram on the left in Figure 8 illustrates the case in which the cost of a feature steadily decreases and willingness to pay extra for it changes. This occurred for electronic control systems for household products. In the past, the price of the electronic system was high and had no obvious added value compared to the traditional control system. As the price of the electronic components decreased over time, and manufacturers learned to use the electronics to add value, customers were finally willing to pay more for an electronic control system than it cost.

The diagram on the right illustrates the case when the price for a feature is stable and the willingness to pay an extra premium varies. This could occur, for example, when changing material from a cheap plastic to a more exclusive material such as stainless steel or wood. The price for the new material is stable over time. However, the willingness to pay extra is strongly influenced by trends; the feature could be popular for awhile and eventually become uninteresting.

3. Methods

3.1. Simulations of the heat pump tumble dryer.

The main purpose to use a heat pump in a tumble dryer is to reduce electricity usage or enable a lower drying temperature if the textiles are sensitive to high temperatures. The performance value used to rate tumble dryers is the total electricity usage and drying time according to a European standard [14]. The best closed cycle heat pump tumble dryers on the market today have the same drying time and use about 64% less electricity compared to a traditional closed cycle condenser tumble dryer. Figure 9 shows the system design of a closed cycle heat pump tumble dryer.

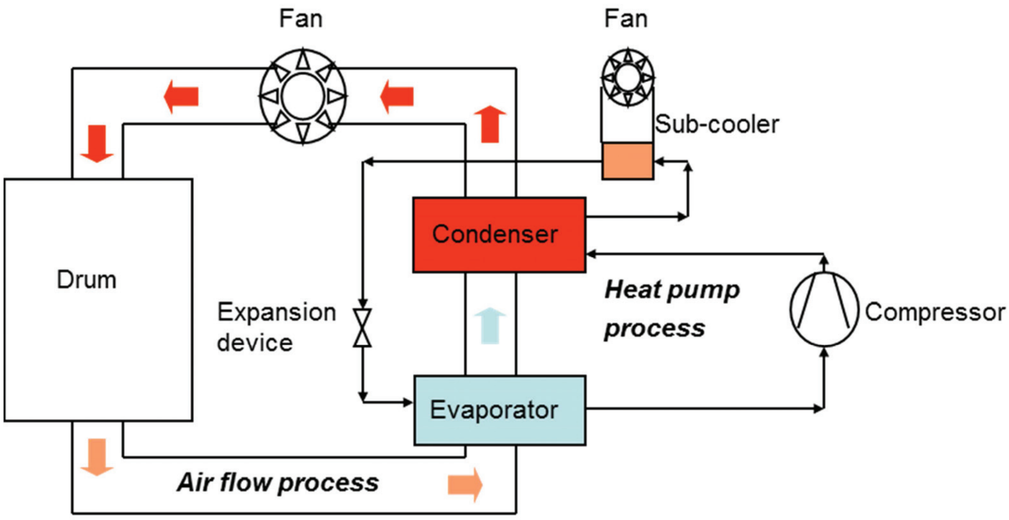

FIG. (9). System design of a closed cycle heat pump tumble dryer.

In practical terms 2.66kWh/cycle (64% reduction) less electricity is needed to dry 7.0kg textiles. This changes the energy label from B to A^{+++} in the EU-energy labelling system. The estimated electricity usage in a modern home with four people in Sweden is 848kWh for the tumble dryer. Replacing a conventional tumble dryer with a dryer with a heat pump system will thus case save about $848 \cdot 0.64 = 543$kWh annually.

On the market today there are many examples of closed cycle heat pump tumble dryers without the sub-cooler and extra fan, shown at the top of Figure 9. Comparing closed cycle heat pump tumble dryers with and without sub-coolers, the electricity usage is slightly lower in cases with the sub-cooler.

In the near future, the focus will probably be on decreasing the drying time. Today, most heat pump tumble dryers use about 1000W electricity power and have the same drying time. In most homes in Europe the maximum permitted electrical power is 2300W. Using the simulation model in Paper I, which describes performed simulations with different size of the compressor, the results in compressor powers were between 1070-1450W. Above 1450W the temperature in the evaporator is under the freezing point, which results in icing. All other conditions are the same as outlined in Paper I.

3.2. Simulations of the heat pump dishwasher.

Some research has been performed to reduce electricity usage of dishwashers. One concept is to use the heat coming from the wastewater of the dishwasher to heat fresh water entering the dishwasher [8]. Calculations and performance tests showed a reduction of 25% in the total electricity usage. By using an additional absorption cycle during the drying process, the total electricity usage was reduced by 25% [9].

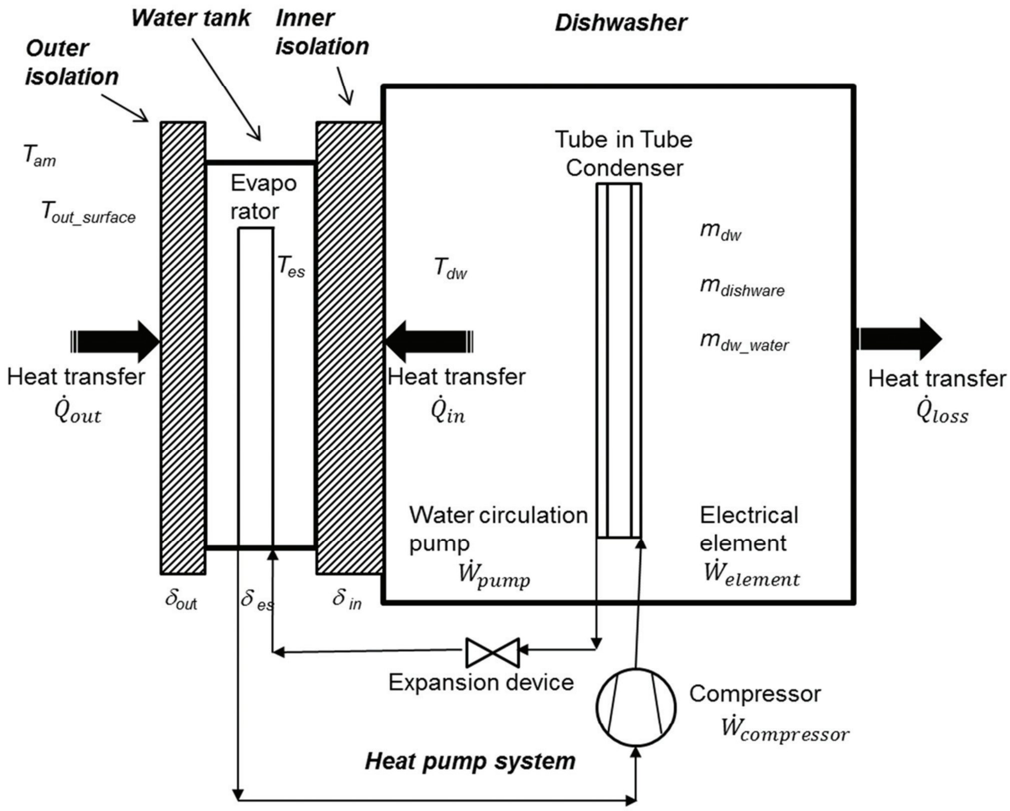

FIG. (10). A dishwasher with an added water tank and heat pump system.

Heating the dishwasher with a hot water circulation loop transfers the energy to the dishwasher via a heat exchanger [10] and replaced up to 90% of the electricity usage to hot water heating. In this case there is no reduction in energy usage, just a change of energy source from electricity to hot water. Another approach is to add a heat pump system where a water tank is the heat source and the dishwasher is the heat sink showed in Paper II (Fig. 10). Most of the heat from the water tank is released when the water freezes. R134a, a hydrofluorocarbon (HFC) refrigerant, was used. The total electricity usage was reduced by 24% compared to a conventional dishwasher, or 0.27kWh/cycle for each washing with a full loaded dishwasher.

The results in the study were based on a prototype of a heat pump dishwasher that was not optimised. There are many parameters that could affect the total electricity usage, for instance the maximum dishwashing temperature, weight of the machine, compressor performance, outer isolation of the cabinet, and the isolation between the dishwasher and the water tank.

Over the last 10 years, in order to decrease the electricity usage the focus has been on decreasing the maximum dishwashing temperature for traditional dishwashers with an electrical element. Simulation was performed with the same simulation model as presented in Paper II to examine how the decreased maximum dishwashing temperature affects the total electricity usage for the heat pump dishwasher. Different maximum dishwashing temperatures between 45-55°C were simulated.

3.3. Calculation of TEWI

For the tumble dryer and the dishwasher TEWI is calculated. It defined the equivalent emission of CO_2 and is defined as:

$$TEWI = GWP \cdot L \cdot n + GWP \cdot m(1-\alpha) + n \cdot E \cdot \beta$$

where L is the leakage rate [kg/year], n is the lifetime [years], m is the refrigerant charge [kg], α is the recycling factor [%], E is the electricity consumption [kWh/year], and β is the emission from electricity generation [kgCO_2/kWh].

The direct part = $GWP \cdot L \cdot n + GWP \cdot m(1-\alpha)$ effect related to refrigerant leakage to the atmosphere and the indirect part = $n \cdot E \cdot \beta$ effect related to the electricity usage of the appliance. Refrigerant 134a was used and the emission from electricity generation was 0.4517kgCO_2/kWh [51] and based from Europe (OECD).

4. Results

The purpose of adding a heat pump system to a dishwasher or a tumble dryer is to increase the value of the product by reducing the electricity usage and the environmental impact. The heat pump system in a tumble dryer, which is common today, is small and uses hermetic compressors and R134a as refrigerant. It is not common to add a heat pump system to dishwashers. Only one example, a dishwasher, is available on the market today.

4.1. Heat pump tumble dryer

The electricity usage decreased from 0.64 to 0.24kWh/cycle kg textiles and the TWEI value from 5745 to 2154kg CO_2 eq. by adding a heat pump system to a conventional tumble dryer.

Heat pump systems in household tumble dryers are common today, and all of the manufacturers have a variant of a heat pump tumble dryer in their product range. The ASKO Appliances AB view of the feature value of the added heat pump system over time is illustrated in Figure 11.

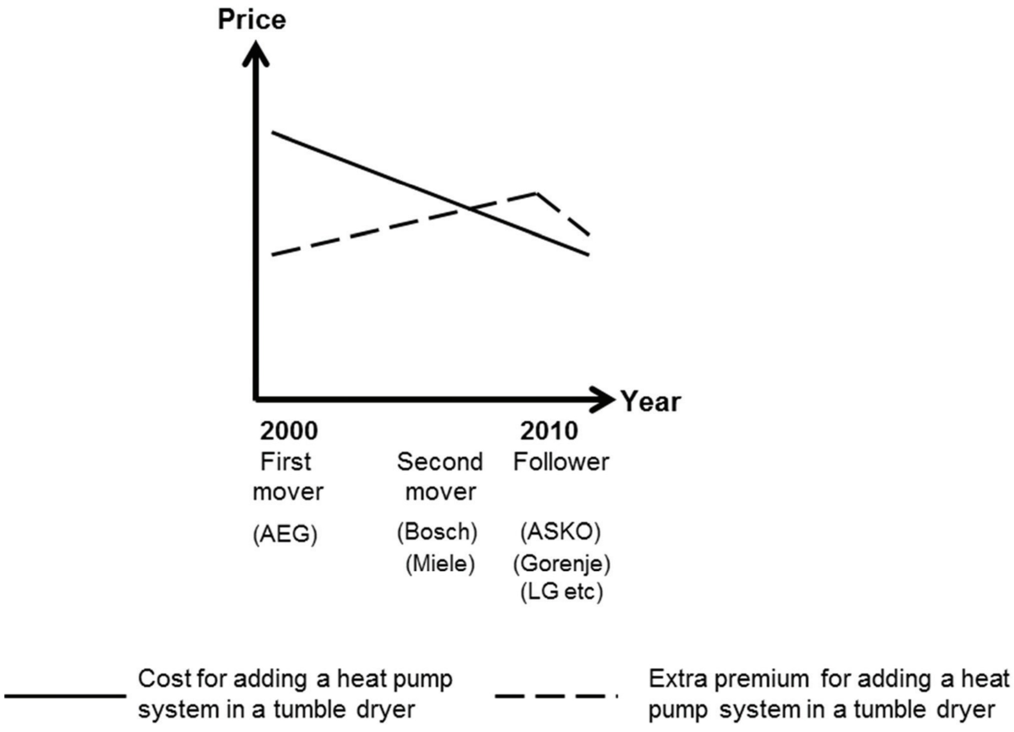

FIG. (11). Cost and extra premium for a tumble dryer, including a heat pump system that decreases the electricity usage and environmental impact. These curves are based on ASKO Appliances AB preconditions.

The price for heat pump components has decreased and seems likely to continue to decrease in the near future. The sales volumes increase, which decreases the cost of the components and the manufacturing. Customers seem to be more interested in reducing electricity usage and the environmental impact, and are also more willing to pay for it. The first mover on the market with a tumble dryer that included a heat pump system was AEG in 2000, and it was expensive. During the 2000s, some second movers introduced less expensive heat pump dryers on the market, and these did well. Today, willingness to pay extra for the heat pump tumble dryer compared to a cheaper traditional dryer is higher than the extra price of the heat pump system. When the heat pump tumble dryer became state-of-the-art customers took the feature for granted and willingness to pay an extra premium decreased. Today, the old types of tumble dryers are even forbidden in some countries, and the only available products on the market are the heat pump tumble dryers.

Results from the simulations with different compressor sizes are shown in Figure 12.

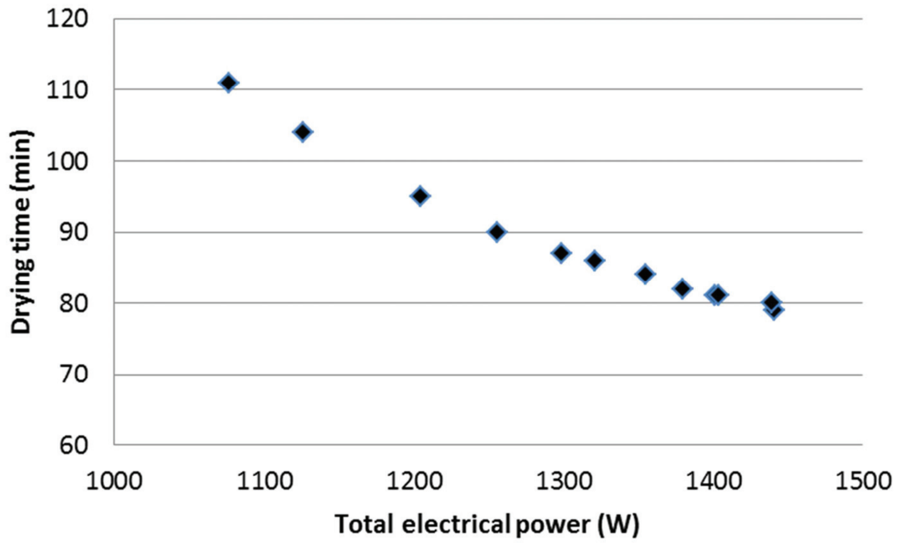

FIG. (12). Drying time from the simulation model with different total electrical powers. The electricity usage was similar with all compressors sizes.

The results showed that it was possible to decrease the drying time with unchanged electricity usage by using a larger compressor. All the other components were the same.

4.2. Heat pump dishwasher

Results from the simulations with different maximum dishwashing temperature are showed in Figure 13.

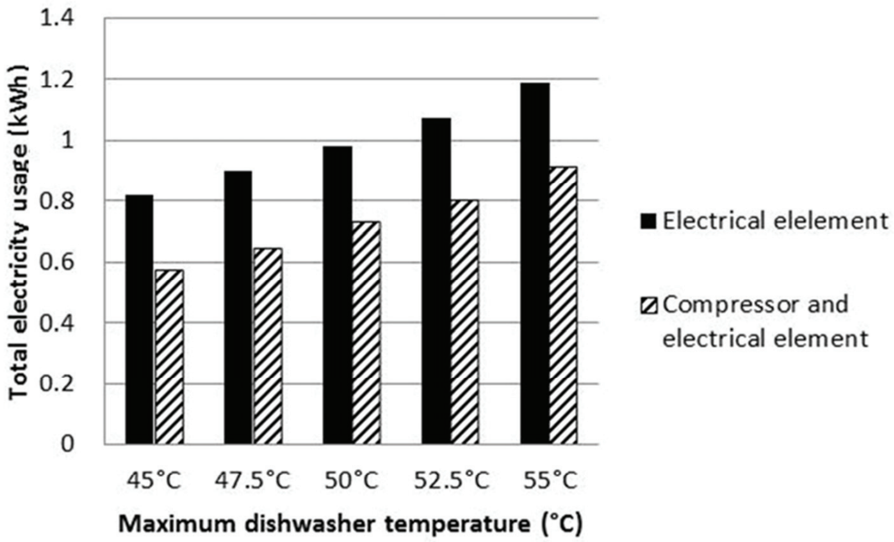

FIG. (13). Simulated total electricity usage of a dishwashing cycle with different maximum dishwasher temperatures. The dishwasher was heated either with only an electrical element or heated with a compressor of $6cm^3$ and an electrical element. The difference between the heating options was about 0.27kWh/cycle in all cases.

Figure 13 shows how large the influence of maximum dishwasher temperature is on the total electricity usage. However, at all temperatures the decreased electricity usage was about 0.27kWh/cycle with the heat pump system compared with using only an electrical element.

Similar parameter studies have been performed with weight of the machine, compressor performance, outer isolation of the cabinet, and the isolation between the dishwasher and the water tank. The results indicate that optimizing these parameters together should be able to decrease the total electricity by an additional 0.03kWh/cycle. A well-optimized heat pump dishwasher could reduce the total electricity usage by about 0.3kWh/cycle. Current dishwashers heated only with an electrical element use about 0.8kWh/cycle. Thus a heat pump dishwasher would use about 0.5kWh/cycle (37% reduction). This would change the energy label from A^{+++} to (A^{+++}–40%) in the EU-energy labelling system for the dishwasher. Replacing a conventional dishwasher with a dishwasher with a heat pump system could save $290 \cdot 0.37 = 108$kWh annually. The TWEI value for a lifetime is decreased from 1965 to 1348kg CO_2 eq. by adding a heat pump system to a conventional dishwasher.

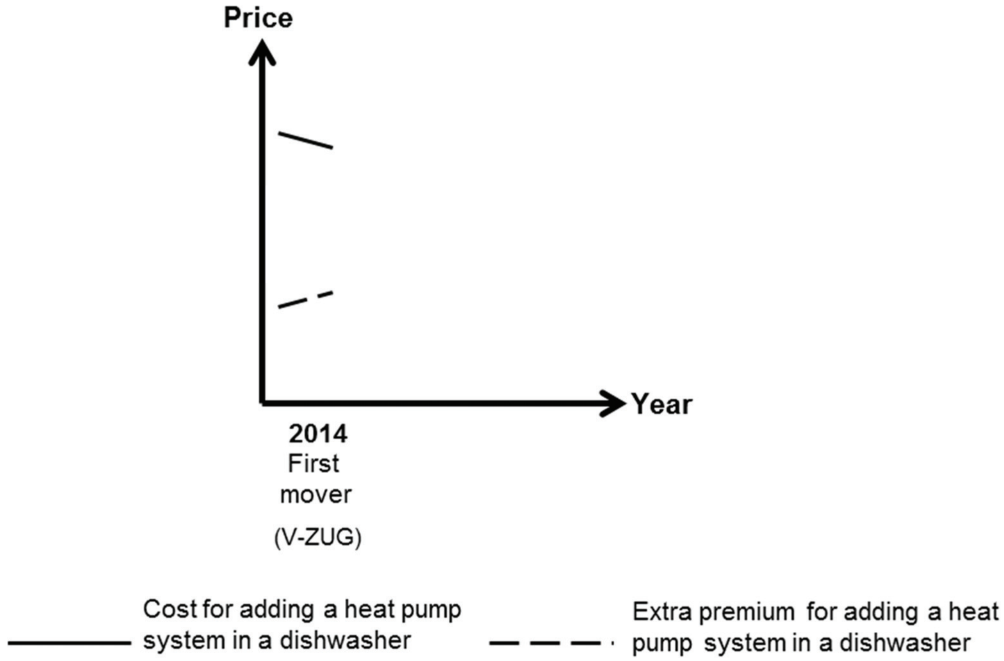

FIG. (14). Cost and extra premium for a dishwasher including a heat pump system which decreases the electricity usage and the environmental impact. These curves are based on ASKO Appliances AB preconditions.

It is hard to predict the willingness to pay an extra premium for this dishwasher in the future. The ASKO Appliances AB view of the feature value of the added heat pump system in the near future is illustrated in Figure 14. Adding a heat pump system has only been implemented in one dishwasher. The first mover was the V-ZUG Adora SL WP model, which appeared on the market in 2014 with the energy label (A^{+++}–40%) in the EU-energy labelling system. By comparison with tumble dryers, heat pump systems have just been introduced to dishwashers. The trend may be the same as for heat pump tumble dryers. The price for heat pump components is decreasing and customers seem to be more interested in reducing electricity usage and environmental impact, while being more willing to pay for it.

5. Summary of Paper I

In the past two types of tumble dryer have dominated the market: open-cycle vented tumble dryers and closed-type condenser tumble dryers. In the late 2000s a new type of tumble dryer was introduced to the market, the heat pump tumble dryer. The advantages of the heat pump tumble dryer are reduced electricity usage of about 64%, and a lower drying temperature.

The competitiveness between the manufacturers of tumble dryers is very strong. Electricity usage and drying time are used when rating and comparing performance between different manufacturers. The main components in a heat pump tumble dryer as drum, drum and fan motor, compressor, condenser, evaporator refrigerant and expansion device affect the performance values.

The aim of this paper is to examine how the size of the compressor (cylinder volume of the compressor) and the condenser (total heat transfer) affect the total electricity usage and drying time for a heat pump tumble dryer.

The behaviour of the process was analysed using a simulation model. An experimental setup based on a state-of-the-art heat pump tumble dryer was developed. How well the simulation model corresponds to the experimental setup is crucial for the reliability of the simulation results. The drying process in a tumble dryer is batch type drying, which means that all the temperatures change during one complete drying cycle. In this type of process a steady-state simulation model cannot represent the drying process well. A transient simulation model of the experimental heat pump tumble dryer was developed in the program Engineering Equation Solver (EES). Simulated results such as the total electricity usage, compressor power and drying time compared well with measurements from the experimental setup.

Cylinder volume of the compressor and the total heat transfer of the condenser were varied in the simulation model. Based on the simulation results, the following conclusions can be drawn:

- When the cylinder volume of the compressor increased by 50%, compared to the experimental setup, the maximum compressor power increased by 14% and the drying time decreased by 14% with unchanged electricity usage.
- A larger compressor satisfies the consumer requirement for a shorter drying time without increasing electricity usage. As space is limited in

the tumble dryer, the compressor should be as large as possible while still fitting in the dryer.

- A transient instead of a steady state simulation model is reflecting the heat pump tumble dryer process in accurate way and gives more reliable results.
- The maximum COP and SMER do not necessarily occur under same operating conditions.

6. Summary of Paper II

When washing dishware in a dishwasher, the majority of the electricity is consumed by the heating of the machine, dishware and water. Currently, the heating is done by an electrical element in most household dishwashers. This paper introduces a method to reduce the total electricity usage by adding a heat pump system and a water tank to the dishwasher. The dishwasher acts as the heat sink, the water tank acts as the heat source, and the majority of the heat transfer to the evaporator occurs when ice is generated in the water tank.

The aim of the paper was to evaluate the potential of this concept to reduce electricity usage without changing the washing time and the maximum washing temperature.

An experimental setup was built based on a conventional dishwasher with an added heat pump system and a water tank. A transient simulation model of a dishwasher with a heat pump system was developed, which compared well with the experimental setup. The cylinder volume of the compressor and the compressor operating time varied in the simulations. Based on the simulation results the following conclusions can be drawn:

- A dishwasher that includes a heat pump system has 24% lower total electricity usage, with the same washing operating time and maximal temperatures in the washing and rinse steps compared to a conventional dishwasher.
- A longer compressor operating time results in lower electricity usage with the same washing time.

This was a concept study using a model based on an experimental setup, which was not a fully developed prototype. By optimising the setup it should be possible to reduce the total electricity usage by more than 24%.

In this paper, the aim did not include changing the total washing operating time or the maximum temperature in the dishwasher cabinet. However, the results showed that it would be possible to reduce the total electricity usage even more by increasing the total washing operating time.

To choose the final combination of components, the washing quality must be studied to determine how different temperatures and washing times affect the washing results.

7. Discussion

In the household industry there are new features introduced on the market all the time. The history of Swedish washing machine manufacturers shows how important it is to adopt and develop the right features, with good quality, and introduce them at the right time. To add new features is always a big risk and that is one reason why manufacturers are restrictive and carful when launching new features. The history of the dishwashing and tumble drying industry in Sweden is the same as for the washing machine.

If a manufacturer is to succeed with a new feature such as the added heat pump system, the following four aspects are important to fulfil:

- Who is launching the feature? The brand story must match the feature.
- All customers must accept the feature.
- There must be incentives for the end consumer to buy the feature.
- There should be no quality problems.

For a new feature to be considered a state-of-the-art solution on the market with large sales volumes it depends on who is launching it. If a large well-known manufacturer introduces a new feature together with a large-scale promotion campaign, and alongside a well-known brand, will the feature be adopted by the customer chain? If they accept the feature will it soon be the state-of-the-art solution that other manufacturers will have to add to their products if they want to compete on the market in the future? If a smaller manufacturer introduces the feature alone will the situation be different? The motive for the manufacturer could be to promote a small-scale niche product for a specific type of end consumer. In this case the manufacturer has no advantages if the feature is a state-of-the-art solution with large volumes on the market. If the volumes are small can the feature be exclusive and the manufacturer can then price it high? In that case, the worst that can happen is that the feature becomes the state-of-the-art solution and selling large volumes, which results in a lower price.

The type of end consumer who will buy a heat pump dishwasher is probably the "high-price shopper" (with high quality and brand preferences for whom price has an important signalling role) [33]. This type of end consumer is willing to pay extra for a brand name and quality [35]. Many of them are also interested in new technical features that may decrease the environmental impact.

Here are three incentives for the end consumer to pay an extra premium for an added heat pump system in a tumble dryer or a dishwasher: decreased electricity bill; better results in the EU-energy labelling system; and reduced environmental impact. These are affecting the cost and extra premium curves in Figure 11 and 14.

Important for an end consumer to buy a tumble dryer or a dishwasher with a heat pump system is to decrease the electricity bill [36]. Changing from a conventional to a heat pump tumble dryer will decrease the electricity usage about 543kWh per year. The savings in money per year due to a reduced electricity bill is significant, and the payoff time is short despite the higher price for the heat pump tumble dryer. The whole customer chain, including all stores, has been informed about the low payoff time in order to convince the end consumer to buy a heat pump tumble dryer rather than a cheaper conventional tumble dryer. The low payoff time and promotions for the customer chain are the main success factors involved in making the heat pump tumble dryer one of the state-of-the-art tumblers dryers today. For heat pump dishwashers the money saved is less because electricity usage over one year is normally lower compared to heat pump tumble dryers. To change from a conventional to a heat pump dishwasher the electricity usage decreases about 108 kWh per year. Even if the price trend is the same as for the heat pump tumble dryer, the savings in electricity usage is less for the heat pump dishwasher compared to the heat pump tumble dryer. Thus, the payoff time is long even if the heat pump dishwasher becomes the state-of-the-art solution and cheaper in the future. The money saved by decreased electricity usage cannot be the sole motive for an end consumer to buy a heat pump dishwasher compared to a conventional variant.

The EU-energy labelling system evaluates and makes it possible to compare products based on, for example, electricity usage. Results from my work showed a reduced electricity usage due to the added heat pump system changes the EU-energy labelling from (A^{+++}) to (A^{+++}–40%) for the dishwasher, and from (B) to (A^{+++}) for the tumble dryer. The EU-energy labelling system makes it easy for the end consumer to compare the energy usage of different brands. Energy label systems are a strong incentive for end consumers when choosing appliances such as tumble dryers and dishwashers [34,36,37].

Surveys show that a large group of end consumers are willing to pay extra for a low impact environmental product [34,37-39]. These surveys outline that environmental awareness is large and will probably increase in the future for a vast number of people. It is not clear what affects the end consumer the most:

the change in the EU-energy labelling system, the decrease electricity bill or the reduced environmental impact. It was a combination of these factors that has made the premium heat pump tumble dryer one of the state-of-the-art dryers alongside vented and condense types. For the heat pump dishwasher to succeed in the future, the entire customer chain should promote the improvement in the values shown in the EU-energy labelling system and the decrease in environmental impact more than the money saved due to decreased electricity usage.

Results from the simulation model of the heat pump tumble dryer show that it is possible to decrease the drying time by using a larger compressor (Figure 12). However, there are problems with a larger compressor, as it can increase the compressor temperature to such an extent that it is too high for the lubricant in the heat pump system. A larger compressor can also decrease the evaporator temperature, risking ice growing on the evaporator surfaces. For the largest compressor in Figure 12, the evaporator temperature was about 0°C during the constant drying period and –20°C at the start. The icing risk can be avoided with larger total heat transfer coefficients (UA value) of the condenser and the evaporator, together with increased airflow. Because of the limited space inside a tumble dryer cabinet it may be difficult to put in larger components. This is a general limitation, and a major challenge for all manufacturers when developing products such as tumble dryers, dishwashers and washing machines. A heat pump tumble dryer with a larger compressor will be more expensive, but will also be attractive to the professional market like textile laundering services where drying time is critical.

The results in Figure 13 show a decreased electricity usage of 0.27kWh/cycle, independent of the maximum dishwashing temperature in a heat pump dishwasher compared to a conventional dishwasher. Simulations showed that to optimise the weight of the machine, compressor performance, outer isolation of the cabinet, and the isolation between the dishwasher and the water tank the electrical usage could decrease to 0.03kWh/cycle more. In the future, there are likely more parameters to optimise the decrease in electricity usage, especially the heat pump components.

There is a possibility to combine the heat pump system with other system by using the heat coming from the wastewater of the dishwasher to heat fresh inlet water [36] or using an additional absorption cycle during the drying process [36]. In reality it could be hard to implement all together because of the limited space, and together they do not provide the sum electrical decrease as they do individually.

Simulations results from Paper II show that the total dishwashing time for a heat pump dishwasher could be longer compared to a conventional dishwasher. This could, of course, be a disadvantage and affect the manufacturers predicted cost and extra premium curves in Figure 14. The end consumer will probably buy the heat pump dishwasher for other reasons, like lower electricity usage and environmental impact. A longer dishwashing time will not be attractive for professional customers such as restaurants, schools and caterers, but the household market is less critical.

The timing for introducing a feature on the market is very important. The risk of failure is larger for the first mover, but so is the opportunity for large profits. For a small manufacturer, with a not so well-known brand, it could be more beneficial to minimise the risk, be a follower, and join the market when the market is ready [42]. For a follower the best timing to introduce a feature is generally when the market is closer to the inflection point in the S-curve where market growth increases rapidly [43], just before it becomes the state-of-the-art solution. In this way a follower will make the best profit. Usually followers enter the market too late and miss the best period for large profits. However, if the feature becomes the state-of-the-art solution manufactures are forced to procure it if they want to be on the market in the future.

ASKO Appliances AB was introduced to the heat pump tumble dryer late and became a follower (see Fig. 12). In hindsight it would probably have been better if the introduction was two to three years earlier when heat pump tumble dryer prices were higher. The inflection point in the S-curve was during those two to three years, a time when the best profit from the feature occurs. The first mover (V-ZUG) is now on the market with a heat pump dishwasher (see Fig. 14). ASKO must choose whether it wants to be the second mover, a follower or not adopt this technology at all [47,48,50]. One question is whether the heat pump dishwasher will become the state-of-the-art solution in the future, like heat pump tumble dryers have become.

In the heat pump industry today it is common to use TEWI to graduating the products by CO_2 equivalent impact, where the refrigerant emission and the electricity usage during its lifetime are included [12,16,30]. In the case of heat pump dishwashers and heat pump tumble dryers, today only the change in the electricity usage affects the EU-energy labelling system. This shows favourable results for the heat pump solutions with refrigerants with high Global Warming Potential such as R134a. However, in the future, when heat pumps are more common in the household industry, a rating based on the total amount of CO_2 impact, such as TEWI, will be practicable and recommended for use.

The competition to have the best performance in the household industry is fierce and pushes the development of better energy-efficient products. What does the future hold for the electricity usage of dishwashers and tumble dryers using today's methods or new methods? For dishwashers, the traditional method of reducing electricity usage is to reduce water use. However, this approach may have reached its limit, with total water usage under 10 litres. Some other examples of decreasing the electricity usage for the dishwasher available on today's market include:

- Lowering the washing temperature;
- Exchanging the heat from the outgoing water with the entering water;
- Lowering the drying temperature by using different methods such as absorption drying or fan systems.

For tumble dryers, the evolution of electricity usage has consisted of mainly technical leaps such as the added heat pump system. The heat pump tumble dryer has only been on the market for about 10 years. Now that it is one of the state-of-the-art solutions the competition between manufacturers will be fierce. Optimising the drying cycle is strongly dependent on using the laws of nature to evaporate water from the textiles. However, there are factors on which manufacturers are focused on to decrease the electricity usage for the heat pump tumble dryer on the market today such as:

- The heat pump components and their configuration;
- Different type of refrigerants;
- Energy losses and leakage in the airflow system.

It is difficult to predict what the next technical leap will be to decrease electricity use and the environmental impact of tumble dryers and dishwashers. The research and the development teams at all of the manufacturers are working hard to develop the next generation of environmentally friendly household appliances.

The project lead time for a large technical feature such as the added heat pump system is two to five years from start to delivery to consumer, and involves large financial and development investments. Starting such a large project is a risk. If the customer chain does not perceive the value of the feature it could be difficult for the manufacturer to survive if it fails. A large manufacturer might be able to withstand the economic loss, but for a smaller manufacturer it could be a catastrophe leading to huge losses and they could disappear from the market. As previously mentioned, this is one of the reasons why some washing machine manufacturers have disappeared.

8. Future studies

Much work is required to develop a series-produced dishwasher with a heat pump system. I would like to point to some areas where more knowledge is needed.

So far only R134a has been considered as the refrigerant. This refrigerant will be phased out in the near future in Europe because of its high global warming potential (GWP) of 1300 [11]. To introduce and promote a heat pump dishwasher with low environmental impact on the market a natural refrigerant with low GWP is preferred. Future work should investigate whether there are any environmentally friendly refrigerants that could be used for the heat pump dishwasher. The natural refrigerants R290 (propane), R600a (isobutene) and R744 (carbon dioxide) are possible alternatives. A theoretical study of how these refrigerant alternatives work in a heat pump dishwasher will be evaluated.

One of these evaluated natural refrigerants will further be evaluated in an experimental setup. This experimental study will be performed in order to define the optimal amount of refrigerant in the heat pump system and the optimum design of the capillary tube.

A dishwashing cycle consists of four steps: prewash, washing, rinse, and drying. In earlier studies, only the washing and rinse steps were studied because most of the electricity usage occurs in these steps. After the rinse step the water tank is full of ice, which could be used in the drying step. The function of the drying is that warm humid air inside the dishwashing cabinet is circulated against the cold surface of the water tank. The water in the air will condense on the cold surface. Practical tests have shown that this works as a drying method. A simulation study will be performed to investigate which parameters to consider and how much they affect the drying performance.

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Increasing the value of household appliances by adding a heat pump system

The competition in the household appliances industry is strong. Manufacturers are continuously trying to develop, produce and sell product functions and features with good profit. To continually develop new features that the customer chain is willing to pay for is a key factor for a manufacturer to survive.

To introduce a new feature the manufacturer must be sure that the customer chain is willing to pay for it from one to five years in the future. In this study has a heat pump system been added as a new feature to the tumble dryer and the dishwasher. The willingness from the customer chain to pay extra for this feature is because of the decreases electricity usage by 64% for the tumble dryer and 37% for the dishwasher. However, the added heat pump system is increasing the price for the machine.

The first heat pump tumble dryer was introduced on the market in 2000 and is currently one of the state-of-the-art variants. This success was mainly because of the money saved from the lower electricity usage. The first heat pump dishwasher was introduced on the market in 2014, but only time will tell if the heat pump variant will dominate in the future.

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