[*]WASTE HEAT RECOVERY IN DISHWASHERS USING LATENT HEAT STORAGE

Bulaşık Makinelerinde Gizli Isı Depolamayla Atık Isı Geri Kazanma

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ABSTRACT

Recently, investigations on improving energy efficiency are getting more important for domestic appliance sector like the other sectors. Studies are carried out to decrease energy and water consumption in dishwashers. Latent heat storage systems can be used for this purpose.

The aim of this study is developing and testing Phase Change Material (PCM) for recovering waste heat in dishwashers. Paraffin based PCMs were chosen to store waste heat from the first washing cycle in dishwashers. In the experimental set-up the stored heat was recovered to be used for pre-heating of the second washing cycle. The maximum temperature increase in the inlet temperature of the second washing cycle was measured as 14.3 ^{o}C and a corresponding increase in energy efficiency as 24.1 %. Thermophysical properties and thermal stabilities of parafin based PCMs and their paraffin binary mixtures with different compositions were determined.

Key Words : Dishwasher, Energy Efficiency, Phase Change Material (PCM), Latent Heat Storage, Waste Heat Recovery

ÖZET

Son dönemlerde, diğer sektörlerde olduğu gibi beyaz eşyalarda enerji verimliliğini artırma üzerine yapılan çalışmalar giderek önem kazanmaktadır. Bulaşık makinelerinde enerji ve su tüketimini azaltmak için çalışmalar yapılmaktadır.

Bu çalışmanın amacı, bulaşık makinelerinde atık ısı kazanma için Faz Değiştiren Madde (FDM) geliştirme ve deneme çalışmalarını gerçekleştirmektir. Bulaşık makinelerinde birinci yıkamadan atık ısı depolamak için parafin içeren FDM'ler seçilmiştir. Deneysel düzenekte, ikinci yıkamanın ön ısıtmasında kullanılmak üzere depolanan ısı geri kazanılmıştır. İkinci yıkamanın giriş sıcaklığındaki maksimum sıcaklık farkı 14,3 ^{o}C olarak ölçülmüş ve buna bağlı olarak enerji verimliliği artışı % 24,1 olarak belirlenmiştir. Parafin içeren FDM'ler ve değişik oranlarda hazırlanan, ikili parafin karışımların termofiziksel özellikleri ve termal kararlılıkları belirlenmiştir.

Anahtar Kelimeler : Bulaşık Makinesi, Enerji Verimliliği, Faz Değiştiren Madde (FDM), Gizli Isı Depolama, Atık Isı Geri Kazanma

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Introduction

Thermal energy storage (TES) systems are used to decrease energy consumption by utilizing renewable energy sources and waste heat. TES is realized as a result of the change in internal energy of a material. One or combination of the following heats is utilized in TES systems: sensible heat, latent heat and/or chemical reaction heat (Dinçer et al., 2002).

Among TES technologies latent heat storage system with phase change material (PCM) is preferred for short term applications of heating and cooling. High storage capacity and isothermal behavior of PCMs make them favorable choices (Abhat,1983; Farid, et al., 2004 and Sharma et al.,2005).

Organic and inorganic materials can be used as PCM for the application of the latent heat storage. Although inorganic PCMs have higher melting enthalpies per volume than organic PCMs, they are corrosive. Moreover, organic PCMs do not show subcooling. The choice of PCM is made considering thermal, mechanical and economical aspects (Mehling et al., 2007).

The latent heat storage can be used to recover waste heat in domestic appliances. Phase change materials which melt at the temperature of waste heat are required for this purpose. There are various ways to increase energy efficiency of domestic appliances. One of them is using waste heat given off while appliance is working.

Gu et al. (2004) developed PCM to recover waste heat rejected from air conditioning system for heating domestic hot water. The outlet temperature of waste heat is approximately 35 ^oC – 45 ^oC for air-conditioning system in this study. Technical grade paraffin wax and mixtures of liquid paraffin and lauric acid were used as PCM (Gu et al., 2004). Buddhi (2003) developed a shell and finned tube type heat exchanger for low temperature industrial waste heat recovery using paraffin wax (m.p. 53.32 ^oC, heat of fusion 184.48 kJ/kg) as PCM. The overall heat transfer coefficient was calculated during charging and discharging process. The overall heat transfer coefficient during charging process was 10-14 W/m^2 ^oC and during discharging was 7-10 W/m^2 ^oC (Buddhi, 2003).

There are few studies on using phase change materials for domestic appliances in literature. In the patent by Longardner and et al. (1993), the design of a PCM heat exchanger for dishwasher and washing machine applications was published. This was a coaxial heat exchanger with two cylindrical chambers inside one another. The inner chamber with PCM was intended to store waste heat from the fluid in the external chamber (Longardner and et al., 1993). In another patent, PCM was used to improve the drying performance of dishwasher. Waste heat of the moist hot air in the drying process is recovered by a heat exchanger with PCM in this patent (Werner, 2000). Azzouz and et al. proposed to increase the energy efficiency of the refrigerator using PCM. It was shown that evaporator temperature can be controlled to increase heat transfer by adding a PCM storage unit near evaporator of refrigerator (Azzouz et al., 2007, 2005). Wang and et al. claimed that the COP of the refrigerator improved 4%-7% by using PCM near condenser of refrigerator (Wang et al., 2007).

In this study, utilization of latent heat storage concept for waste heat recovery in dishwashers was investigated. Thermophysical properties and thermal stability of appropriate PCMs were determined. The PCMs were tested in an experimental TES unit designed for dishwashers to evaluate their performance for increasing energy efficiency.

Material and Method

Determining Phase Change Temperature

The washing cycles of dishwasher presented schematically in Figure 1 were investigated to determine temperature of waste heat storage and recovery. In the first washing cycle 4 L water charged to the system is heated to 52ºC for washing and then is discharged at 42ºC from the system. The following areas were determined according to the first washing cycle in dishwasher for waste heat storage:

- I. Area indicated as “a” in Figure 1, waste heat at temperature 52ºC
- II. Area indicated as “b” in Figure 1, waste heat at temperature 42ºC

In the second washing cycle 3L water is supplied to the system and water temperature is increased from 23ºC to 60ºC. Waste heat stored in the first washing cycle will be used with the purpose of reducing energy consumption for heating 3L water in the second washing cycle. The area for waste heat recovery in the washing cycle of dishwasher is shown as “c” in Figure 1.

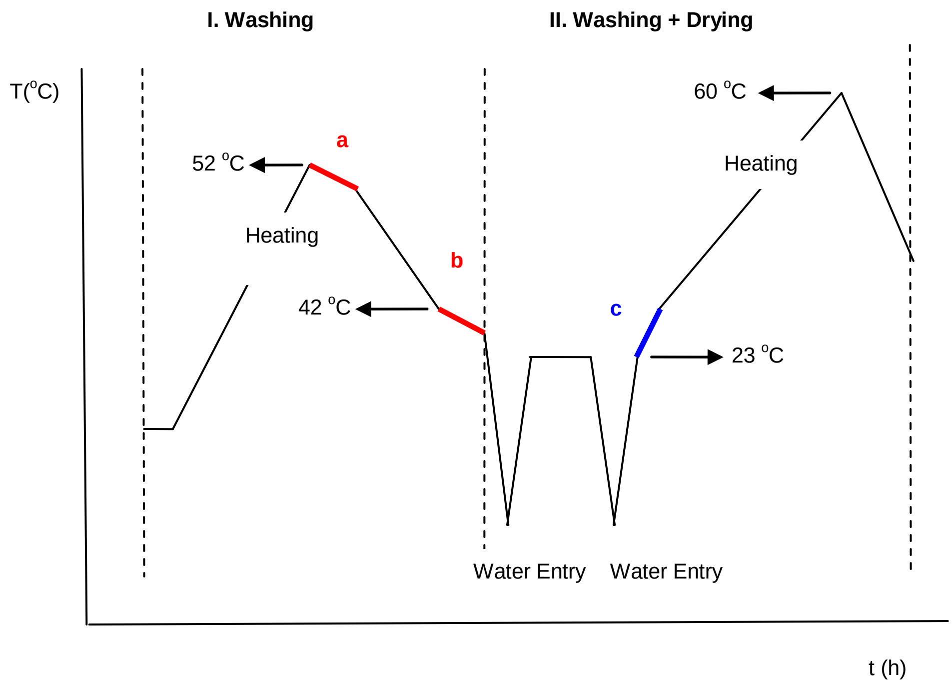

Figure 1. Washing cycles temperature-time diagram of dishwasher (a, b: waste heat storage, c: waste heat recovery)

Development of PCMs

PCMs changing phase at temperature intervals a or b as shown in Figure 1 and having high storage capacity are needed to store waste heat in dishwasher. For this purpose, PCMs with phase change temperatures in the range of 35°C–50°C were investigated. PCMs with this melting temperature range are paraffins, fatty acids, salt hydrates and eutectic mixtures. Fatty acids and salt hydrates are eliminated due to their corrosive effects. Salt hydrates also have problems such as melting incongruently and subcooling.

Paraffins were chosen as the best candidates for PCMs for this system with their benefits such as high storage capacity, non-toxic and non-corrosive effect, thermal and chemical stability. The following paraffins were tested as phase change materials (PCM) according to the waste heat temperature of dishwashers:

1. Commercial PCMs:
   - RT42 (Melting Point 43 °C) – Rubitherm, Germany – PCM-A
   - E32 (Melting Point 32 °C) – EPS, United Kingdom – PCM-B
2. Pure Materials
   - Paraffin (Melting Point 42 – 44 °C) – Merck – PCM-C
   - Paraffin (Melting Point 46 – 48 °C) – Merck – PCM-D
   - Paraffin (Melting Point 56 – 58 °C) – Merck – PCM-E

Determination of Thermal Properties and Stability of PCMs

During waste heat storage and recovery process, melting and freezing cycle of PCM is called as thermal cycling. While numbers of thermal cycling of PCM are increasing, thermal and chemical stability of material must not change. For this reason, thermal stabilities of the PCMs were determined with 1000 thermal cycling tests in this study. The thermophysical properties of the PCMs at the end of 0, 100, 200, 400, 600, 800, and 1000 cycles were determined by analyzing with DSC (Perkin Elmer-Diamond Model). The scanning rate was 10ºC/min. for the measurements.

Experimental Set-up of Waste Heat Storage and Recovery

The experimental set-up used is shown schematically in Figure 2. Thermostatic water bath was used to simulate waste heat from the first washing cycle of dishwasher. Heat exchangers for the TES unit were designed according to the availability of free volume in the dishwasher. Two different copper tube type finned multi-pass heat exchangers were used as TES unit. For waste heat recovery a water reservoir of 3 L volume was used. Temperature at the inlet, outlet and inside the heat exchanger were measured and recorded by a data acquisition and control system with an accuracy of ±0.4ºC. Duration of storage and recovery periods was 10 min and 15 min, respectively.

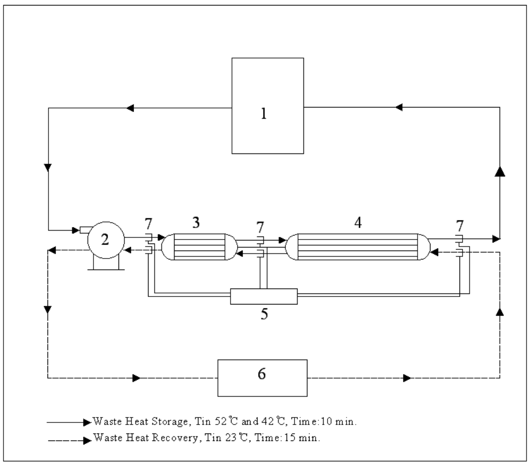

Figure 2. Schematic figure of waste heat storage and recovery of experimental set up (1: Water Bath, 2: Circulation Pump, 3: Heat-exchanger1, 4: Heat-exchanger2, 5: Data-Logger,

Research and Discussion

Thermal cycling tests to determine thermal stability of the PCMs determined with suitable melting ranges were carried out. Before thermal cycles the thermophysical properties of PCMs determined by DSC are shown in Table 1. Based on DSC results, the following mixtures were determined as candidate PCMs for dishwasher prototype and thermal cycles of these materials were done: Mixture of 20 % PCM-D – 80 % PCM-C (PCM-F), PCM-C and PCM-A.

Table 1. DSC Analyses results of PCMs before thermal cycles

PCM	Latent Heat of Fusion ΔH (J/g)	Melting Temperature Tm (^oC)
PCM-B	102	33 – 43
PCM-C	137	39 – 47
PCM-D	135	41 – 49
PCM-A	130	39 – 49
90% PCM-D - 10% PCM-C	132	41 – 51
80% PCM-D - 20% PCM-C	131	40 – 49
70% PCM-D - 30% PCM-C	129	39 – 48
60% PCM-D - 40% PCM-C	130	39 – 47
50% PCM-D - 50% PCM-C	129	39 – 48
40% PCM-D - 60% PCM-C	135	39 – 47
30% PCM-D - 70% PCM-C	131	39 – 47
20% PCM-D - 80% PCM-C	131	39 – 46
10% PCM-D - 90% PCM-C	131	39 – 47
10% PCM-E - 90% PCM-C	128	38 – 48
20% PCM-E - 80% PCM-C	133	39 – 48
30% PCM-E - 70% PCM-C	127	39 – 49
40% PCM-E - 60% PCM-C	127	39 – 52
50% PCM-E - 50% PCM-C	128	39 – 53
60% PCM-E - 40% PCM-C	119	40 – 55
70% PCM-E - 30% PCM-C	117	42 – 57
80% PCM-E - 20% PCM-C	118	45 – 58
90% PCM-E - 10% PCM-C	125	47 – 59

For PCM-C, PCM-F and PCM-A 1000 thermal cycles and DSC analyses were repeated.Three analyses were done for each PCM. Values of standard deviation in latent heat of fusion shown in Table 2 are from ±5.7 to ±7.8. Standard deviations of latent heat of fusion of DSC analyses indicate that PCMs chosen for dishwasher application have acceptable thermal stability.

Table 2 Results of DSC analyses repeated for PCM-C, PCM-F and PCM-A after 1000 thermal cycles

PCM	Latent Heat of Fusion ΔH (J/g)	Melting Temperature Tm (^oC)	Average Latent Heat of Fusion - Standard Deviation
PCM-C (0-1)	126	38-44	126 J/g ±5.7
PCM-C (0-2)	135	38-44	
PCM-C (0-3)	135	37-45	
PCM-C (100-1)	121	38-44	
PCM-C (100-2)	123	38-44	
PCM-C (100-3)	111	37-44	
PCM-C (200-1)	126	37-44	
PCM-C (200-2)	121	37-43	

PCM-C (200-3)	125	37-44	
PCM-C (400-1)	126	38-44	
PCM-C (400-2)	128	38-44	
PCM-C (400-3)	120	38-44	
PCM-C (600-1)	131	38-44	
PCM-C (600-2)	127	38-44	
PCM-C (600-3)	128	38-44	
PCM-C (800-1)	134	38-44	
PCM-C (800-2)	128	38-45	
PCM-C (800-3)	129	38-44	
PCM-C (1000-1)	124	37-44	
PCM-C (1000-2)	119	38-44	
PCM-C (1000-3)	127	38-44	
PCM-F (0-1)	133	37-45	
PCM-F (0-2)	128	38-45	
PCM-F (0-3)	128	38-45	
PCM-F (100-1)	114	38-45	
PCM-F (100-2)	124	38-45	
PCM-F (100-3)	108	38-44	
PCM-F (200-1)	128	37-45	
PCM-F (200-2)	132	38-45	
PCM-F (200-3)	127	38-45	
PCM-F (400-1)	115	38-45	126 J/g ±7.8
PCM-F (400-2)	131	38-45	
PCM-F (400-3)	134	38-44	
PCM-F (600-1)	129	38-44	
PCM-F (600-2)	134	38-45	
PCM-F (600-3)	128	38-45	
PCM-F (800-1)	115	38-45	
PCM-F (800-2)	128	38-45	
PCM-F (800-3)	136	38-45	
PCM-F (1000-1)	134	38-45	
PCM-F (1000-2)	130	38-45	
PCM-F (1000-3)	118	38-45	
PCM-A (0-1)	137	38-47	
PCM-A (0-2)	106	37-47	
PCM-A (0-3)	111	37-47	
PCM-A (100-1)	116	37-47	
PCM-A (100-2)	117	37-46	
PCM-A (100-3)	115	37-46	
PCM-A (200-1)	117	38-47	
PCM-A (200-2)	117	37-46	117 J/g± 6.6
PCM-A (200-3)	115	37-47	
PCM-A (400-1)	114	37-46	
PCM-A (400-2)	110	37-46	
PCM-A (400-3)	117	37-47	
PCM-A (600-1)	128	37-47	
PCM-A (600-2)	117	38-47	
PCM-A (600-3)	123	37-47	
PCM-A (800-1)	109	38-47	
PCM-A (800-2)	119	38-47	

PCM-A (800-3)	119	38-48	
PCM-A (1000-1)	119	37-47	
PCM-A (1000-2)	118	37-47	
PCM-A (1000-3)	112	38-47	

PCM-expanded graphite composite in planar form was prepared for PCM-A. Waste heat storage and recovery experiments were repeated for 52ºC waste heat temperature. Inlet and outlet temperatures of PCM-A were plotted with respect to time in Figure 3. Moreover, comparison of temperature differences of inlet and outlet are compared in Figure 4 for PCM-expanded graphite composite in the granular form and in the planar form for PCM-A at 52^{o}C. The temperature difference increased from 12.8 ºC to 14.3 ºC, when heat exchanger1 and 2 with expanded graphite in the planar form were used together.

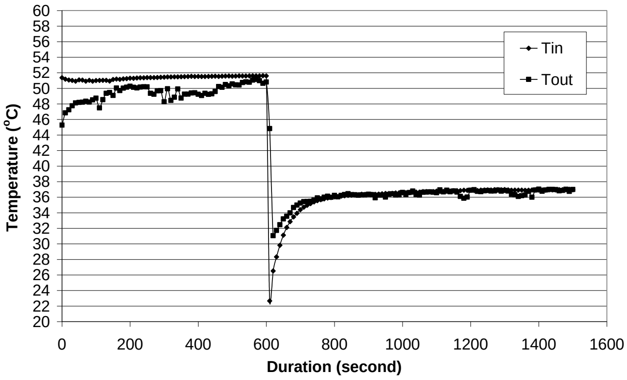

Figure 3. Inlet and outlet temperatures with respect to time for PCM-A with planar form expanded graphite during waste heat storage and recovery for 52 ^{o}C waste heat temperature and with insulated heat-exchanger1 and 2

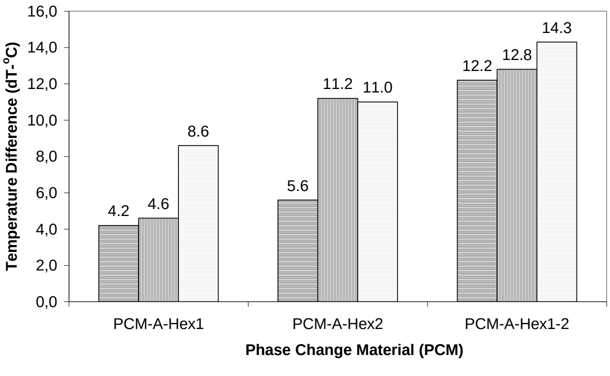

Figure 4. Comparison of temperature differences obtained in the insulated medium at 52 ^{o}C waste heat temperature by using different types expanded graphite for PCM-A (Horizontal Dash: PCM without graphite, Vertical Dash: PCM with graphite in granular form, Point: PCM

with graphite in planar form, Hex1: Heat-Exchanger1, Hex2: Heat-Exchanger2, Hex1-2: Heat-Exchanger1 and Heat-Exchanger2 together)

The maximum temperature difference of 14.3^{o}C was measured for PCM-A at 52 ºC storage temperature. The corresponding calculated increases in energy efficiency of the dishwasher for different PCMs tested at the storage temperature of 52 ºC are compared in Figure 5. The increases in energy efficiencies calculated were between 24.1 % and 10.3 %.

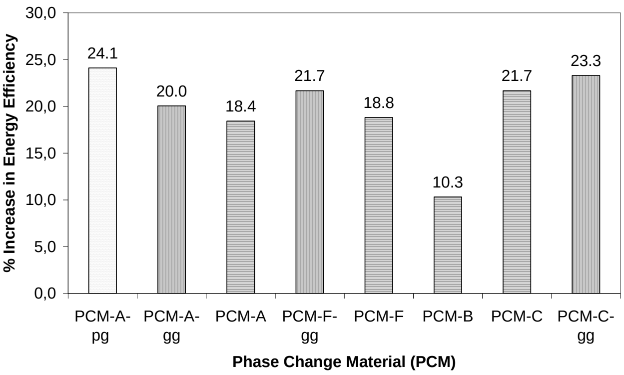

Figure 5. % increase in energy efficiency of the dishwasher for different PCMs tested at the storage temperature of 52 ºC

Conclusion

In this study, two different commercial PCMs (PCM-A-Rubitherm-Germany and PCM-B-EPS-United Kingdom) and binary mixtures of analytic grade paraffins (PCM-C, PCM-D, and PCM-E-Merck) were developed and tested to utilize waste heat and to increase energy efficiency in dishwashers. Paraffins are non-toxic materials and are chemically inert and stable. They can melt congruently with no subcooling and preferred for latent heat storage systems as PCM due to their good chemical and physical properties. These properties of paraffins were the reasons for choosing them as PCMs in this study.

PCM-A, PCM-C and PCM-F were determined as the most suitable PCMs after thermal stability tests for waste heat temperatures of 42 ^{o}C and 52 ^{o}C. Expanded graphite was used in granular and planar forms for PCM-A. The maximum increase in temperature difference between inlet and outlet in waste heat recovery experiments for PCM with expanded graphite in the granular form was only 0.6 ^{o}C, while the maximum increase in temperature difference obtained when PCM with expanded graphite in the planar form was 2.1 ^{o}C. The maximum temperature increase in the inlet temperature of the second washing cycle was measured as 14.3^{o}C when PCM-A with expanded graphite in planar form was used. The corresponding increase in energy efficiency of dishwasher was calculated as 24.1 %.

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