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Application of Exergy Analysis to Textile Printing Process

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Abstract
This study reveals an exergetic analysis of the reactive and pigment printing processes. Exergy models of the printing processes were formed and each step examined in terms of exergetic parameters. In the printing machine, the reactive printing process led to a higher specific exergy use due to the penetration requirement of the printing paste. The exergy efficiency in the subsequent drying after printing was found to be independent of the printing method, but affected by the fabric structure, which was calculated to be between 3.8% and 4.8%. In the fixation step, pigment printing provided the highest exergy efficiency, calculated to be 2.15%, due to the direct heating of the fixation air. It was observed for the fixation step that the boiler unit of the steaming process and the burner of the hot air fixation process led to the highest exergy destruction rates. The total exergy destruction rate in pigment printing was found to be higher than in the washing and final drying stages of reactive printing alone; thus, it was shown that the exergetic improvement of the post-washing and drying of reactive printing is of great importance.

Key words: *exergy analysis, textile printing, steaming, hot air fixation, exergy destruction.*

Nomenclature

C	*specific heat in kJ/kgK*
$\dot{E}$	*energy rate in kJ/s*
$\dot{E}x$	*exergy rate in kJ/s or kW*
ex	*specific exergy in kJ/kg*
h	*specific enthalpy in kJ/kg*
$\dot{Y}$	*irreversibility rate in kJ/s*
LHV	*lower heating value in kJ/kg*
$\dot{m}$	*mass flow rate in kg/s*
P	*pressure in kPa*
$\dot{Q}$	*heat transfer rate in kW*
R	*universal ideal gas constant in kJ/kgK*
s	*specific entropy in kJ/kgK*
$\dot{S}_{gen}$	*entropy generation rate*
T	*temperature in °C or K*
$\dot{W}$	*work rate or power in kW*
ω	*humidity ratio of air*
ε	*exergy efficiency*
φ	*constant for industrial fuels*

Subscripts

0	*dead state*
a	*dry air*
ch	*chemical*
cr	*convection and radiation*
d	*destruction*
e	*exit*
f	*fuel*
i	*inlet*
l	*loss*
ma	*moist air*
p	*constant pressure*
q	*heat transfer related*
w	*water*
$\cdot$	*rate*
v	*vapor*

Introduction

Exergy analysis is an efficient method to analyze the performance of thermal systems by using the second law of thermodynamics as well as the mass and energy balances. The formal definition of exergy is given [1 - 5] as 'the maximum amount of useful work that can be obtained as the system is brought to equilibrium with the environment'. Similar to energy, exergy has components such as physical, chemical, kinetic, and potential; however, unlike energy, exergy is not conserved because it is destroyed in any actual process. Exergy destruction directly caused by the irreversibilities is related to the entropy production.

The method of exergy analysis defines the irreversibilities of the system and brings out to what extent the exergy is destroyed in every sub-system of an actual process. The exergy analysis directly detects the inefficiencies of the system, and the outputs of the analysis can be suitable for the improvement of systems in terms of efficient energy use. Therefore exergy analysis has begun to be used as an advanced thermodynamic method for thermal systems [6], which enables the location, cause and true magnitude of the sources destroyed [1].

Recently many studies on exergy analysis have been performed. Some of the studies (i.e. [7 - 11]) investigated sector-specific analyses of a whole country, while others focused on a specific system. Exergy analysis was applied to a variety of industrial processes such as distillation [12], cogeneration [13], food drying [14, 15], geothermal heating [16], etc. There are also methodology based studies on exergy analysis. Szargut [17] presented a sequence method for analysis of exergy losses in thermal systems using the index of the cumulative consumption of exergy. Dincer and Sahin [18] investigated a thermodynamic model for drying processes. Textile technology applications of exergy analysis, however, are still inadequate and limited. In previous studies the exergy analysis of textile drying [19 - 21] and dyeing processes [22] were studied using exergy models. Mozes et al. [23] investigated the conventional textile washing process by using cumulative exergy consumption data. On the other hand, no studies have appeared in literature on the exergy analysis of textile printing processes, which was the prime motivation behind performing the present study.

In the textile industry, the majority of all printed substrates are cellulosic fabrics [24, 25], for which pigment printing and reactive printing methods are widely used. Textile printing is a complex process and it is very difficult to control all the process parameters [26] Pigment printing stands out with its simplicity of application [27, 28] and it is advantageous in terms of energy and water savings since the process does not involves post-washing steps after fixation with high temperatures of dry air. On the other hand, reactive printing requires sequential washing and rinsing steps in order to achieve the quality standards, which means higher energy consumption. Reactive dyes have gained an importance in textile printing because of their high fastness properties and brilliant colours [29]. In this study, exergy analyses of pigment

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Table 1. Properties of the fabrics.

Abbreviation	Type	Mass per unit area, kg/m²	Width, m	Printing speed, m/min
REAC1	11.8/1 tex, single jersey	0.095	1.6	40
REAC2	29.5/1 tex, single jersey	0.200	1.8	30
PIGM1	29.5/1 tex, double jersey	0.280	2.0	50
PIGM2	19.7/1 tex, single jersey	0.150	1.5	55

Table 2. Washing recipes after reactive printing.

Light shades	Medium shades	Dark shades
Rinsing, at room temp, 15 min		
Washing, 95 °C, 15 min		
one step	two steps	three steps
Rinsing, at room temp, 15 min		
Neutralisation and softening		

and reactive printing on cotton fabrics were investigated. The main purpose of the study was to create a practical model for exergy analysis of printing processes by using measured operational data. By using detailed and sub-system involved control volumes of each machine and giving numerical data on exergy destruction and exergy efficiency of the units of the printing process, the exergy map of the total printing process could be evaluated for a general overview.

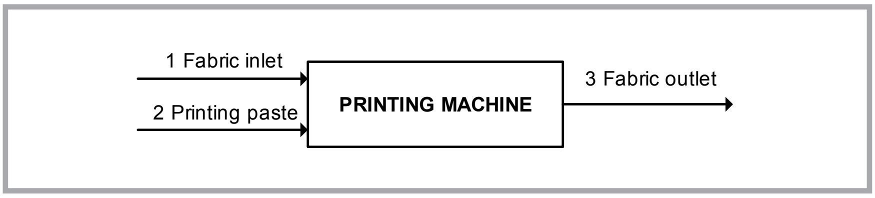

Figure 1. Control volume of printing machine.

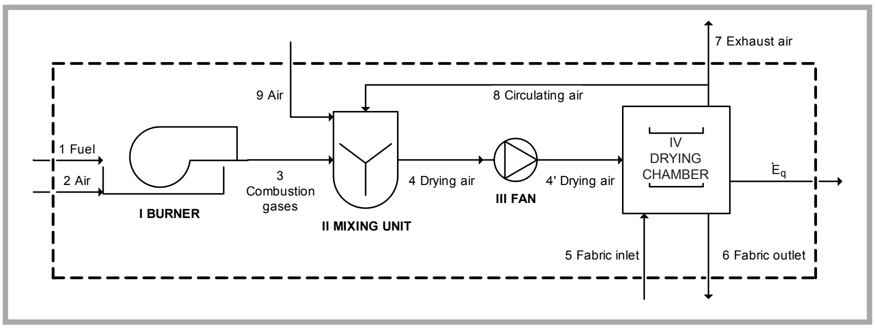

Figure 2. Control volume of drying units (used both for drying after printing, and after washing) [21].

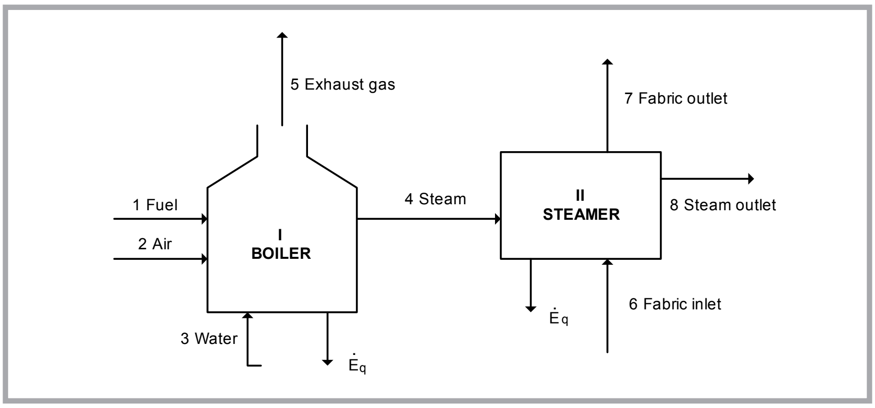

Figure 3. Control volume of steamer.

Analysis

Exergy analyses of the reactive and pigment printing processes were conducted with the help of actual operational data obtained in textile printing mills. 100% cotton knitted fabrics were used throughout the analyses, the properties of which are given in ***Table 1***. The reactive printing process includes printing, drying, fixation with saturated steam, washing and drying steps. After printing with a Reggiani Unica rotary screen printing machine, the fabrics were dried at 130 °C, and fixated with saturated steam at 102 °C for 10 min, in a Salvade VPM steamer. The fixated fabrics were washed in an overflow dyeing machine and dried at 150 °C in a direct gas heated stenter. The washing recipes are given in ***Table 2***. The same machine course was used for pigment printing; however, the pigment printing process did not involve washing and subsequent drying steps. The fixation of pigment printed fabrics was carried out at 150 °C for 10 min with hot air. The control volumes constituted for each step of printing including input and output data are shown in ***Figures 1 - 5***.

The following assumptions were made during the analysis:

a) All processes are steady state and steady flow with negligible kinetic and potential energy effects.
b) Heat transfer to the system and work transfer from the system are positive.
c) Ideal gas principles were applied to the air and exhaust gases.
d) Combustion reaction in the burner is complete.
e) The temperature, relative humidity and pressure of the dead state are taken as the actual ambient conditions (20 °C and 101.325 kPa).

Considering the assumptions above, mass, energy and exergy balances for any steady-state system can be written as:

$$\sum \dot{m}_i = \sum \dot{m}_e \qquad (1)$$

$$\sum \dot{E}_i - \sum \dot{E}_e = 0 \qquad (2)$$

$$\sum \dot{E}x_i - \sum \dot{E}x_e = \sum \dot{E}x_d \qquad (3)$$

The specific flow exergy is determined as:

$$ex = (h - h_0) - T_0(s - s_0) \qquad (4)$$

where h is the specific enthalpy, s the specific entropy, and the subscript zero indicates properties at the reference (dead) state.

The exergy rate is expressed as:

$$\dot{E}x = \dot{m} \cdot ex \qquad (5)$$

Considering dry air and water vapour as an ideal gas, Wepfer *et al*. [30] developed the following relation for the specific physical exergy of the moist air:

$$ex_{ma} = (C_{p,a} + \omega C_{a,v})(T - T_0 + -T_0 \ln\frac{T}{T_0}) + (1+\tilde{\omega})R_a T_0 \ln\frac{P}{P_0} + R_a T_0\left[(1+\tilde{\omega})\ln\frac{1+\tilde{\omega}_0}{1+\tilde{\omega}} + \tilde{\omega}\ln\frac{\tilde{\omega}}{\tilde{\omega}_0}\right] \qquad (6)$$

where

$$\tilde{\omega} = 1.608\omega \qquad (6a)$$

$$\tilde{\omega}_0 = 1.608\omega_0 \qquad (6b)$$

$$\omega = \dot{m}_v / \dot{m}a \qquad (6c)$$

The net exergy transfer by heat at temperature T is given by

$$\dot{E}x_q = (1 - \frac{T_0}{T})\dot{Q}_{\varepsilon} \qquad (7)$$

where T is the temperature at which the heat transfer takes place and $\dot{Q}_{\varepsilon}$ is the heat transferred by convection and radiation.

The specific chemical exergy of the fuel (natural gas) was calculated by the following relation [2]:

$$ex_{ch} = (LHV) \cdot \varphi \qquad (8)$$

where φ is the ratio of chemical exergy to the lower heating value of fuels, selected as 1.04 for natural gas [2].

The entropy balance can be evaluated as:

$$\dot{S}_i - \dot{S}_e = \dot{S}_{gen} \qquad (9)$$

where, $(\dot{S}_i - \dot{S}_e)$ is the net entropy transfer rate, and $\dot{S}_{gen}$ the entropy generation rate. The entropy generation rate is calculated as:

$$\dot{S}_{gen} = \sum \dot{m}_e s_e - \sum \dot{m}_i s_i - \sum \frac{\dot{Q}}{T} \qquad (10)$$

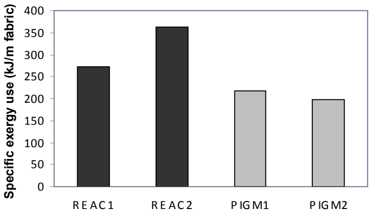

Figure 6. *Specific exergy use values in printing machine.*

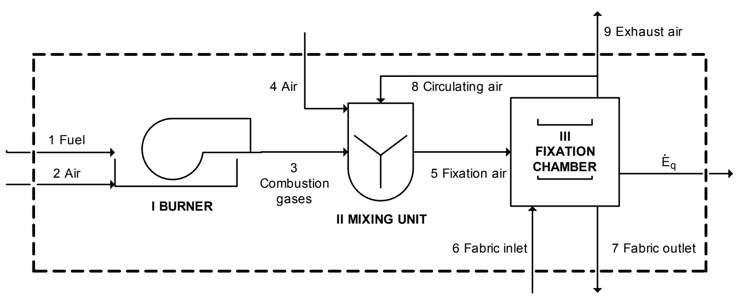

Figure 4. *Control volume of hot air fixation.*

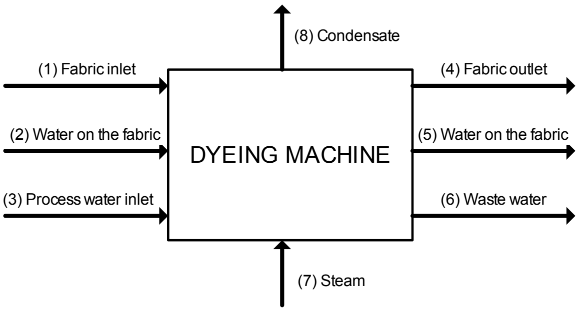

Figure 5. *Control volume of washing [22].*

where $\dot{Q}$ is the heat transfer rate. The irreversibility rate, namely the exergy destruction rate can be expressed for steady-state open systems as

$$\dot{I} = T_o \dot{S}_{gen} \qquad (11)$$

where T_o is the dead state temperature.

Mass, energy and exergy balance relations for each step of the printing process are indicated in ***Table 3*** according to the control volumes given in ***Figures 1 - 5***.

The first law efficiency is not adequate to measure the performance of the actual systems. Thus the second law efficiency is defined as the performance criteria of systems under reversible conditions for the same final states [31]. The exergy efficiency of the systems was calculated by the following equation:

$$\varepsilon = (1 - \frac{\dot{E}x_d + \dot{E}x_l}{\dot{E}x_i}) \cdot 100 \qquad (12)$$

Results and discussion

The specific exergy use values (kJ/m) of the printing machine for each type of fabric and processes are illustrated in ***Figure 6*** . It is clear that the exergy use in the reactive printing process is higher than that of pigment printing. In the reactive printing process, the penetration of the printing paste into the reverse side of the fabric is of importance. Therefore the fabric passing velocity is lower compared with pigment printing, thus leading to an increase in specific exergy use. The penetration rate is directly affected by the viscosity of the printing paste, fabric structure and fibre type. Thus in order to obtain adequate penetration rates, the velocity should be decreased for high weighted fabrics, which results in higher specific exergy use. Since pigment printing is connected with the surface of the fabric, the difference in fabric weight does not have a significant effect on specific exergy use in the printing machine.

Figure *7* shows the exergy destruction rates and exergy efficiency of the subse-

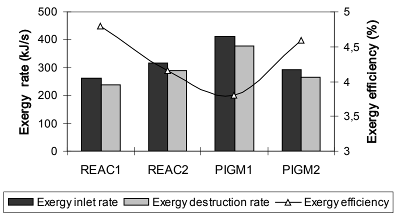

Figure 7. *Exergy inlet and destruction rate and exergy efficiency of the drying process after printing.*

Table 3. *Mass, energy and exergy balances of each step in printing processes; * The model presented by Cay et al. [21] was used for the control volume and exergy balances of drying processes. ** The specific exergy use and specific exergy destructions were used for the exergy balance. The model presented by Cay et al. [22] was used.*

Unit		Mass, energy and exergy balance relations	
Printing machine		$\dot{m}_1 + \dot{m}_3 = \dot{m}_2$	(13a)
		$\dot{E}_1 + \dot{E}_3 + \dot{W} = \dot{E}_2$	(13b)
		$\dot{E}x_1 + \dot{E}x_3 + \dot{W} = \dot{E}x_2 + \dot{E}x_d$	(13c)
Drying machine*	Burners	$\dot{m}_1 + \dot{m}_2 = \dot{m}_3$	(14a)
		$\dot{E}_1 + \dot{E}_2 = \dot{E}_3$	(14b)
		$\dot{E}x_1 + \dot{E}x_2 = \dot{E}x_3 + \dot{E}x_{d,I}$	(14c)
	Mixing	$\dot{m}_3 + \dot{m}_8(\omega_8 + 1) + \dot{m}_9(\omega_9 + 1) = \dot{m}_4(\omega_4 + 1)$	(15a)
		$\dot{E}_3 + \dot{E}_8 + \dot{E}_9 = \dot{E}_4$	(15b)
		$\dot{E}x_3 + \dot{E}x_8 + \dot{E}x_9 = \dot{E}x_4 + \dot{E}x_{d,I}$	(15c)
	Circulating fans	$\dot{m}_4(\omega_4 + 1) = \dot{m}_{4'}(\omega_{4'} + 1)$	(16a)
		$\dot{E}_4 + \dot{W}_{fan} = \dot{E}_{4'}$	(16b)
		$\dot{E}x_4 + \dot{W}_{fan} = \dot{E}x_{4'} + \dot{E}x_{d,III}$	(16c)
	Drying chambers	$\dot{m}_{4'}(\omega_{4'} + 1) + \dot{m}_5 = \dot{m}_6 + \dot{m}_7(\omega_8 + 1) + \dot{m}_8(\omega_9 + 1)$	(17a)
		$\dot{E}_{4'} + \dot{E}_5 = \dot{E}_6 + \dot{E}_7 + \dot{E}_8 + \dot{E}_q$	(17b)
		$\dot{E}x_{4'} + \dot{E}x_5 = \dot{E}x_6 + \dot{E}x_7 + \dot{E}x_8 + \dot{E}x_q + \dot{E}x_{d,V}$	(17c)
Steaming	Boiler	$\dot{m}_1 + \dot{m}_2 + \dot{m}_3 = \dot{m}_4 + \dot{m}_5$	(18a)
		$\dot{E}_1 + \dot{E}_2 = \dot{E}_3 + \dot{E}_4 + \dot{E}_5 + \dot{E}_q$	(18b)
		$\dot{E}x_1 + \dot{E}x_2 + \dot{E}x_3 = \dot{E}x_4 + \dot{E}x_5 + \dot{E}x_q + \dot{E}x_{d,I}$	(18c)
	Steamer	$\dot{m}_4 + \dot{m}_6 = \dot{m}_7 + \dot{m}_8$	(19a)
		$\dot{E}_4 + \dot{E}_6 + \dot{W} = \dot{E}_7 + \dot{E}_8 + \dot{E}_q$	(19b)
		$\dot{E}x_4 + \dot{E}x_6 + \dot{W} = \dot{E}x_7 + \dot{E}x_8 + \dot{E}x_q + \dot{E}x_{d,I}$	(19c)
Fixation	Burners	$\dot{m}_1 + \dot{m}_2 = \dot{m}_3$	(20a)
		$\dot{E}_1 + \dot{E}_2 = \dot{E}_3$	(20b)
		$\dot{E}x_1 + \dot{E}x_2 = \dot{E}x_3 + \dot{E}x_{d,I}$	(20c)
	Mixing	$\dot{m}_3 + \dot{m}_4 + \dot{m}_8 = \dot{m}_5$	(21a)
		$\dot{E}_3 + \dot{E}_4 + \dot{E}_8 = \dot{E}_5$	(21b)
		$\dot{E}x_3 + \dot{E}x_4 + \dot{E}x_8 = \dot{E}x_5 + \dot{E}x_{d,I}$	(21c)
	Fixation chamber	$\dot{m}_5 + \dot{m}_6 = \dot{m}_7 + \dot{m}_8 + \dot{m}_9$	(22a)
		$\dot{E}_5 + \dot{E}_6 + \dot{W} = \dot{E}_7 + \dot{E}_8 + \dot{E}_9 + \dot{E}_q$	(22b)
		$\dot{E}x_5 + \dot{E}x_6 + \dot{W} = \dot{E}x_7 + \dot{E}x_8 + \dot{E}x_q + \dot{E}x_{d,III}$	(22c)
Washing**		$m_1 + m_2 + m_3 + m_7 = m_4 + m_5 + m_6 + m_8$	(23a)
		$E_1 + E_2 + E_3 + E_7 + W = E_4 + E_5 + E_6 + E_8 + E_q$	(23b)
		$Ex_1 + Ex_2 + Ex_3 + Ex_7 + W = Ex_4 + Ex_5 + Ex_8 + Ex_q + Ex_d$	(23c)

quent convective drying after the printing step. A small amount of water is transferred to the textile fabrics during the printing process as compared with other application methods, such as exhaustion or impregnation. Hence energy consumption in the subsequent dryer integrated into the printing machine step is quite low. On the other hand, it is important that a considerable amount of the exergy inlet to the drying process be destroyed, as shown in the figure. Appropriate reduction possibilities of exergy destruction rates in textile dryers were studied extensively in previous studies [20, 32].

Since the water is removed by heat energy, the fabric structure and moisture content in the fabric are the basic parameters in the energy consumption of drying processes. It was observed that the exergy use and destruction rates are similar for single-jersey fabrics, although they were treated with different printing methods. The double-jersey fabric resulted in higher exergy destruction rates. As expected, subsequent drying process after printing were not affected by the printing method in terms of exergy,with the fabric structure being the dominant factor. The exergy efficiency of the subsequent drying after printing was calculated to be between 3.8% and 4.8%, and the double-jersey fabric led to the lowest exergy efficiency value.

The fixation of the reactive printed samples was processed in a steamer connected to a steam boiler. Thus not only the steamer but also the boiler were included in the analysis, and it was observed that a drastic amount of exergy was destroyed in the boiler compared with the steamer unit, as shown in ***Figure 8***, which is because the combustion process is an important source of irreversibility. Conversely, in the steamer unit, steam contacts with the fabric and leads to an irreversibility simply due to heat transfer by both convection and condensation. It is clear that the exergy destruction rate of the boiler constitutes the main part of the total destruction resulting in the steaming system.

Figure 9 shows the exergy destruction and exergy loss rates of the hot air fixation process after pigment printing. The burner causes the highest exergy destruction rates due to the irreversibilities of the combustion process. The exergy destruction rate in the mixing unit of the system is also high. It was observed that the irreversibility in the fixation process with hot air was affected by the fabric weight, with the exergy destruction rate increasing with an increase in the weight of the fabric.

Along with the exergy destruction rate, that of the exergy loss is an also important factor for exergetic investigation of the processes. The steaming process led to a higher exergy loss compared with hot air fixation, due to both the stack gases from the boiler and exhaust steam from the steamer.

Figure 10 represents a comparison of the total exergy destruction rates and exergy efficiencies of the fixation processes. It is obvious that exergy destruction in the steaming of reactive printing was higher than in the hot air fixation of pigment printing. The difference occurs due to the variation in the heating elements. In hot air fixation, the energy required for the heating of fixation air is produced within the machine due to the direct gas heating

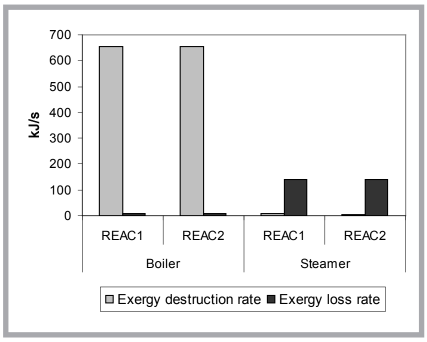

Figure 8. Exergy destruction and exergy loss rate of the steaming process of reactive printing.

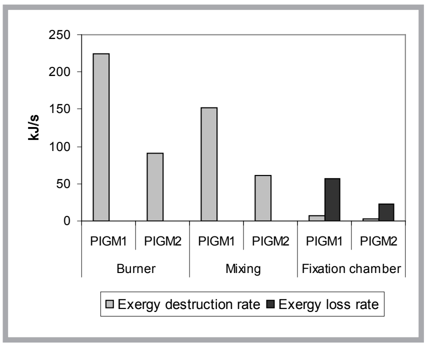

Figure 9. Exergy destruction and exergy loss rate of the hot air fixation process of pigment printing in each component.

system, whereas indirect heating is used in the steamer system. The exergy destruction rate of the boiler system is quite high compared with the burner of hot air fixation, because in addition to the combustion process, steam production leads to irreversibility due to the indirect heat transfer as well. The exergy efficiencies of the fixation processes were found to be 0.25 - 0.58% for the steaming of reactive prints and 2.15% for the hot air fixation of pigment prints.

The pigment printing process ends after the fixation step; however, the washing step should be applied for reactive printed fabrics in order to remove unfixed and hydrolysed reactive dyes. As mentioned before, the number of washing steps is directly related to the shade of the printing. ***Figure 11*** shows the specific exergy use, specific exergy destruction and specific exergy loss of washing processes for the fabrics in different shades. It was observed that the shade of printing is analogous with the exergetic values by a linear relationship.

Figure 12 represents the specific exergy use in each step of the reactive and pigment printing processes. It is shown that the highest specific exergy use in reactive printing occurs due to the steaming, washing and final drying steps. For pigment printing, the fixation step is the most energy intensive of the whole process. As is known, the total energy consumption in pigment printing is lower compared with reactive printing, because the process does not involve washing and final drying steps. It is interesting that the total specific exergy use in the washing and final drying processes in reactive printing alone is substantially higher than the specific exergy use in the whole pigment printing process.

Conclusions

This study comprised an exergy analysis of the reactive and pigment printing processes. For this purpose, the control volumes of each step were constituted and exergy balances formed. The main conclusions drawn from the results of the study are listed as follows:

- The specific exergy use in the printing machine is higher for reactive printing due to lower passing velocities, providing adequate penetration of the printing paste into the reverse side of the fabric.
- The exergy use and destruction rate in the drying stage after printing mainly depend on the fabric structure and are not affected by the printing method. The exergy efficiency of the subsequent drying after printing was calculated to be between 3.8% and 4.8%.
- In the steaming of reactive prints, the boiler unit formed the highest exergy destruction rates. The burner unit of the hot air fixation led to the highest exergy destruction rates for the hot air fixation process. Thus optimization of the combustion processes and reducing fuel use are of great importance for reduced irreversibility.
- The exergy efficiencies of the fixation processes were found to be 0.25 - 0.58% for the steaming of reactive prints and 2.15% for the hot air fixation of pigment prints. The hot air fixation process is more efficient because the exergy destruction in the steaming of reactive printing was higher than in the hot air fixation of pigment printing due to the indirect heat transfer in the boiler.

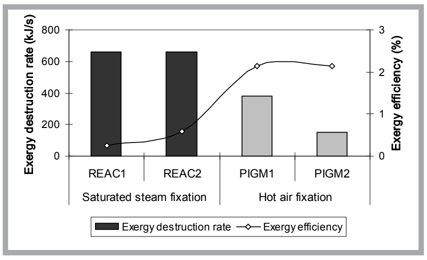

Figure 10. Total exergy destruction rate and exergy efficiency of fixation processes.

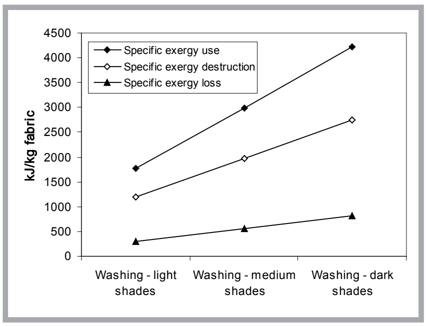

Figure 11. Exergetic evaluation of washing processes.

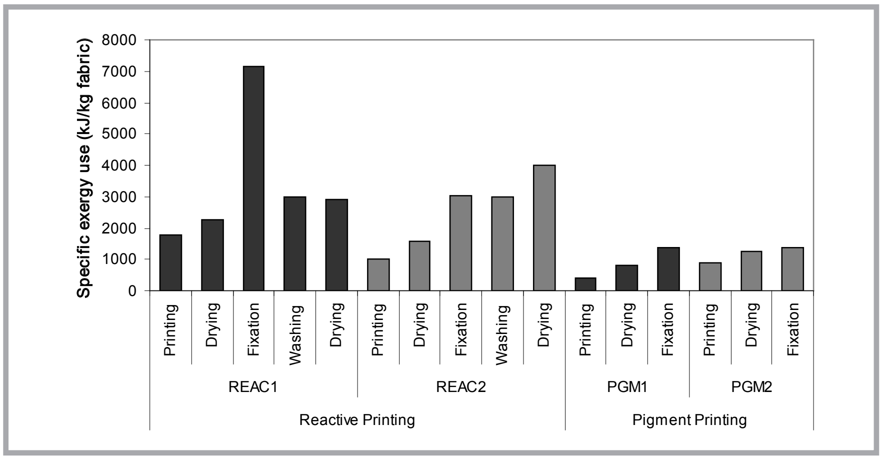

Figure 12. Specific exergy use in each step of printing process.

- The exergy destruction and loss rate in the washing step have a linear relationship with the shade of the printing.
- The total specific exergy use is rather higher for reactive printing. The total specific exergy use in the washing and final drying processes in reactive printing alone is substantially higher than the specific exergy use in the whole pigment printing process.
- It was concluded that the fixation and drying steps of the printing process generally caused the highest irreversibilities, thus in practice more attention should be given to this equipment in terms of energy consumption. By developing an energy management system and applying energy efficiency measures to thermal printing equipment such as improving the combustion efficiency, decreasing heat loss by inslulation, heat recovery, etc., the exergy destruction and exergy loss could be decreased.

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