Experimental Analysis of Gas Consumption Applying Indirect Heating in Fabric Drying Processes

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Drying is one of the most energy-consuming process in textile processing. with energy expenditures up to 25% of the total production energy requirements. It serves to reduce the moisture content in textile products after wet processing. Energy savings in drying process using fabric stenters with indirect heating system using hot oil boiler and thermal fluid distribution system have been calculated. The heat and mass transfer by blowing heated air through the humid textile material leads to the moisture of the material being transferred to the air. The system was calculated using various system combinations to increase system efficiency and reduce fuel consumption. Applying processes using recuperation, recirculation and combination of both to increase drying efficiency could optimize drying techniques based on thermal energy. Those energy-savings also result in improvements of the production process with respect to environment. Fuel savings with indirect heating system show fuel savings over the real process of 26.06% with recirculative, 30.86% with recuperative and 41.34% with combined process.
Keywords: *fabric drying stenters, fuel savings, direct heating*

1. Introduction

The drying of textile products is generally considered as one of the most energy consuming operations with 25% of the wet processing energy being used for drying [1]. To point out, during finishing stages in fabric production, fabrics are treated in average twice or more times by convective stenter drying machines [2].

The stenter drying machines are types of dryers used to remove excess moisture from various samples such as yarns (packages, tops, hanks, loose stock) and fabrics. They are mainly used in finishing process for heat-setting, curing, drying, thermosol processes and finishing of fabrics. They also affect the final dimensional stability adding to the length and width by widen them and correct distortions in the weft. The stenter system is formed by combining up to 10 modular drying chambers, each one automated with individual temperature control. Fabric is transversely tensioned and fitted by clips to system of chains. It is carried through system of drying chamber by endless traveling chains on tracks at velocities between 0.17 and 1.7 m/s. Hot air nozzles create uniform induced draft of air. The hot air is blown inside the chambers by system of induced draft fans against the fabric and then recirculated. The air is distributed on both upper and lower side of the moving fabric at speeds ranging from 10 to 100 m/s and temperatures ranging from 100 to 350°C [3]. Production capacities excee-

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ding 100 kg/h often require continuous dryers, such as stenters [4,5].

2. Stenter system with indirect thermal fluid heating system

Thermal stenter dryers are usually used in final drying because of the limitations of mechanical dryers. Those convective dryers are suitable for drying textiles with drying medium being hot air flowing through porous textiles and forcing evaporation of moisture. In the through-air drying process, high energy is required for heating air and blowing it through the wet material [1,3]. In this papers system modification of stenter system will be shown in regard to indirect heating system. Stenters can be heated in two major ways, indirectly and directly. Through the past, the stenters were mainly heated indirectly by steam transferred from boilers. But this system, although fairly simple and affordable, couldn't keep up with temperature requirements. From their development in 1990's, the thermal fluid systems have been used as an industrial heating system in which a special heat transfer liquid is recirculated by a pump through a fired heat exchanger and used in process heating [6]. Since the beginning of the 21st century, widely used heating system for textile drying stenters is thermal fluid system, which is also indirect heating system [5,7]. A thermal fluid or hot oil system is an industrial heating system in which a special heat transfer liquid is recirculated by a pump through a fired heat exchanger and used in process heating. The two systems have major differences in both implementation and working principle. Indirect heating system by thermal fluid requires hot oil boiler and large heat exchangers and thus uses extra space. The advantage includes operating flexibility, allowing the change of drying parameters, lower maintenance costs, continuous working principle without interrupting production cycle, auxiliary fuel supply. Except having lower maintenance cost, the service of such indirect heating systems requires extensive work and a lot of time. If the system is maintained in the proper manner it will allow low operating costs and fewer production interruptions, but those systems have higher implementation costs compared to the direct heating systems. Significant decrease in energy efficiency is the result of unburned fuel in both systems if not operated properly. The indirect heating systems allow continuous operation and thus higher production [8]. Plants operating by fuel-burned boilers however have extensive heat losses due to high fuel moisture content, incomplete combustion in fuel burner, losses in boiler tubing, high stack gas temperature, heat losses in the steam distribution network and condensate return pipes to the boiler. The energy efficiency of such indirect heating systems is 75%–87% [9].

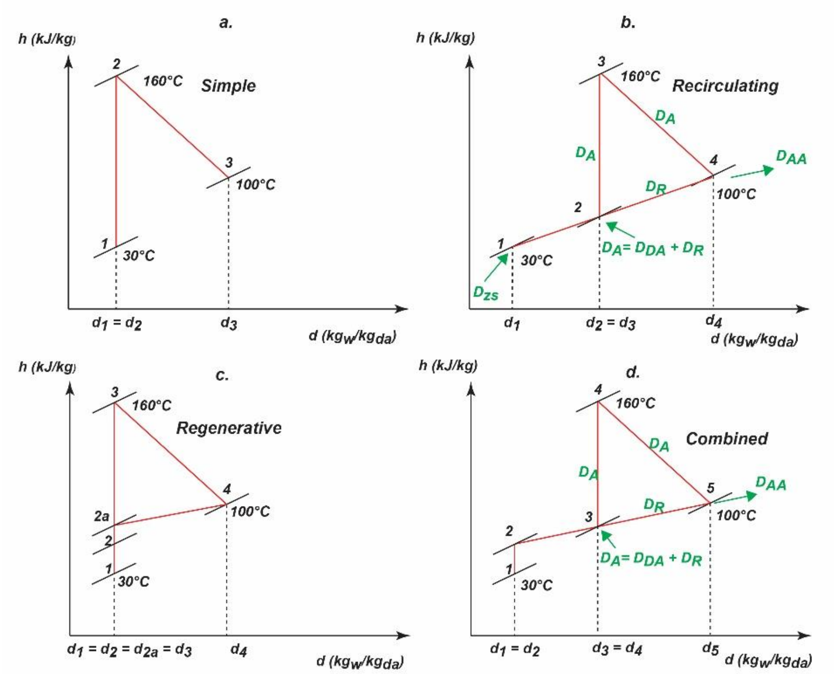

Fig.1 Schematic representation of stenter processes a) simple, b) recirculating, c) recuperative (regenerative) and d) combined

2.1. Stenter system modifications regarding heat recovery process

The paper presents the experimental calculation of annual fuel consumption (m^3, tEU) and a comparison of savings for the following processes, fig.1 a) Conventional drying process and b) Recirculative drying process with air recirculation. The exhaust air should be used in heat recovery systems to preheat the drying air in order to reduce natural gas consumption in the stenter as seen in c) Recuperative drying process with recuperator and d) Combined drying process utilizing both recirculation and recuperative heat recovery.

As seen in fig.1a) simple conventional drying process involves atmospheric air entering the process and being heated by heaters at constant moisture content ($d_1=d_2$). After reaching the temperature (t_2), the hot air is directed into the dryer to evaporate the moisture from the wet material under con-

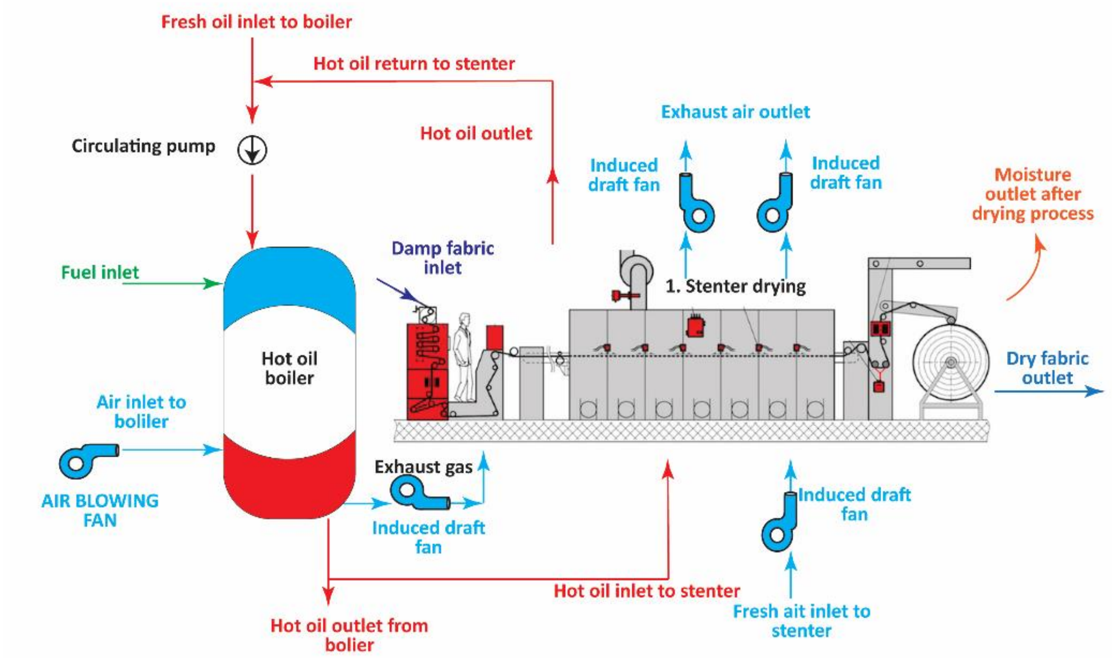

Fig.2 Stenter drying process with indirect heating

stant enthalpy (stage 2 to 3). Recirculative drying process (b) involves part of the air from the dryer returning to the process, and being mixed with ambient air (stage 2). Recuperative (regenerative) drying process with recuperator (c) utilizes the exhaust air heat recovery. The hot air returning from the dryer is transferred to process via recuperator, to transfers the heat to incoming fresh air (stage 2) and the heating and drying process continues as described in conventional drying. Combined drying process utilizes both recirculation and recuperative heat recovery (d). The fresh air with ambient temperature enters the recuperator using fans, where it is heated at constant moisture content ($d_1=d_2$) by the process air stream leaving the dryer. The mixing point is shown in point 3 at the process diagram. After transferring the heat to fresh air, the process air stream is exhaust to the environment at much lowered temperature (point 6). Point 3 to 4 present the heating process, while 4 to 5 present the drying process.

3. Experimental analysis of potential energy savings in stenters with indirect heating system

At the end of the pre-drying phase, a damp cloth with a reduced moisture content enters the device for continuous fabric drying with a conveyor belt and a blower of hot air - conveyor belt drying machine. Energy calculations refer to the drying process in a continuous dryer, i.e. a stenter drying machine [9]. The presented stenter has six connected modular chambers, each with four fans for hot air circulation. The air is heated by hot oil coming out of the boiler (or directly from direct gas burners) and serves as a heat carrier. In first proposed system, the boiler does not heat the water turning it into hot steam, but servers as hot oil boiler, which then transfers the heat to the drying air and circulates through the continuous drying system by means of pumps, fig.2. In hot oil boilers (thermal heaters, shell boilers) special thermal oil circulates as a heat carrier and the system can operate at low operating pressures up to 6 bar with high temperatures up to 300°C. This cannot be achieved if the heat carrier is water or steam, because such system would require achieving a high operating pressure of 85 bar at a temperature of 300°C [10]. Therefore, achieving high temperatures at relatively low operating pressures is the biggest advantage of hot oil boilers and are therefore suitable for use in industrial processes. Drying air and flue gases are released further into the atmosphere. Gaseous fuel enters the boiler at a temperature 240°C and a pressure of 324 kPa. The second part of the fuel that enters the boiler is returned from the production process at a temperature of 200°C. The temperature of the fabric at the entrance to the continuous dryer is 30°C and the pressure of 101.33 kPa, and at the exit of the dryer 65°C and the pressure of 101.33 kPa. The flue gas temperature at the boiler outlet is 428°C. The temperature of the humid air at the outlet of the dryer is 115°C. The temperature of the hot oil at the outlet of the boiler (heat exchanger), ie. at the inlet to the continuous dryer, is 240°C. Heat energy for heating is obtainned by combustion of gaseous fuel that has a lower calorific value H_n = 35649 kJ/m^3, and the boiler efficiency is η_B= 87%. Oil is used as a heat exchanger, and the heat transfer efficiency from oil to air is η_h= 80%. The plant works 8 h in day, 25 days in month (operating time, τ=8 h/day= 2920 h/year).

In a stenter with a plant use factor of β = 50.4%, 300 kg/h of material with an initial humidity of 65% to a final humidity of 8% are dried. The mass of water evaporated from the fabric passing through the dryer [10] calculated acc. (1) from the wet material moisture content (x_i), material moisture content after drying (x_o) and the mass of material entering the stenter (D_{DF}). The enthalpy is calculated acc. (2) with known air inlet temperature of 25°C, relative humidity 60% and moisture content d_1=0.008 $kg_{H_2O}/kg_{dry\ air}$, enthalpy of 45.4 kJ/kg can be either read from Ramzin enthalpy-moisture (*h,d*) diagram or calculated as (3). The air consumption is calculated as (4) [10].

Since the ambient air at the inlet to the heater has the temperature of 25°C, relative humidity 60% and moisture content d_1=0.008 $kg_{H_2O}/kg_{dry\ air}$, and heating proceeds up to 160°C. The temperature of the humid air at the outlet of the dryer is 100°C. The atmospheric air is initially heated in the heater at constant moisture (d_1=d_2) from t_1 to t_2 giving the enthalpy difference h_2-h_1, which represents the amount of heat spent for heating1 kg of air, fig.1a. After that, the hot air with temperature t_2 is directed to the dryer to evaporate the moisture from material at constant enthalpy h_2=h_3, however the moisture content is raised from d_2=0.008 $kg_{H_2O}/kg_{dry\ air}$ to d_3=0.03 $kg_{H_2O}/kg_{dry\ air}$, as seen in Ramzin enthalpy-moisture (*h,d*) diagram, fig.1a.

$$D_{H_2O}=D_{Mvu}\cdot[(x_u-x_i)/(100-x_i)]=300\cdot[(65-8)/(100-8)]=185.9\ kg/h \quad (1)$$

$$h_1=t_{a1}+(2500+1.96\cdot t_{a1})\cdot d_1=25+(2500+1.96\cdot 25)\cdot 0.008=45.4\ kJ/kg \quad (2)$$

$$h_2=t_{a2}+(2500+1.96\cdot t_{a2})\cdot d_2=160+(2500+1.96\cdot 160)\cdot 0.008=182.5\ kJ/kg \quad (3)$$

$$D_z=D_{H_2O}/(d_3-d_2)=185.9/(0.03-0.008)=8450\ kg/h \quad (4)$$

$$q_t=(h_2-h_1)/(d_3-d_2)=(182.5-45.4)/(0.03-0.008)=6231.8\ kJ/kg_{H_2O} \quad (5)$$

$$Q_t=D_{H_2O}\cdot q_t=185.9\cdot 6231.8=1\ 158\ 491.6\ kJ/h \quad (6)$$

$$Q'_t=Q_t/(\eta_B\cdot\eta_h)=1\ 158\ 491.6/(0.87\cdot 0.8)=1\ 664\ 499.4\ kJ/h \quad (7)$$

$$V_g=Q'_t/H_n=1\ 664\ 499.4/35649=46.7\ m^3/h \quad (8)$$

$$V_{gg}=V_g\cdot\tau=46.7\cdot 1471.7=68\ 728.4\ m^3/year \quad (9)$$

$$Q_g=Q'_t\cdot\tau=1\ 664\ 499.4\cdot 1471.7=2.45\cdot 10^9\ kJ/year \quad (10)$$

$$Q_{tEU}=Q_g/29.3\cdot 10^6=2.45\cdot 10^9/29.3\cdot 10^6=83.6\ TCE \quad (11)$$

The difference d_3-d_2 is the quantity of moisture evaporated per kg of air ($kg_{H_2O}/kg_{dry\ air}$). From operating data, energy requirements in theoretical process can be calculated. In the presented continuous dryer produces, 185.9 kg/h of moisture (D_{H_2O}) is evaporated after drying 300 kg/h of damp material, thus producing dry material containing 8% of water. In order to do so, 8450 kg/h of dry air (D_a) is needed to lower the fabric humidity from 65% to 8%.

3.1. Conventional drying process with indirect heating system

The amount of specific heat needed to evaporate moisture from the fabric is calculated as (5), the total heat consumption as (6), The required heat energy with losses considered (η_B= 87%) and (η_h= 80%) as (7), fuel volume consumption per hour calculated from required heat energy and the lower calorific value of gaseous fuel H_n = 35649 kJ/m^3 as (8), yearly operating time (τ) with a plant use factor of β=50.4% as τ=β·2920=0.504·2920=1471.7 h, yearly fuel volume consumption as (9), the total yearly heat consumption as (10) and the total yearly heat consumption in tonne of coal equivalent (TCE) as (11).

3.2. Recirculative drying process with air recirculation of Y_O=53%

Mass of ambient fresh air mixing with the humid air stream is calculated as (12), humidity ratio of air leaving the stenter as (13), humidity ratio of air at mixing point between humid process and ambient air stream as (14), enthalpy of moist air leaving stenter as (15), temperature of air at mixing point between humid process and ambient air stream as (16), enthalpy of air at mixing point between humid process and ambient air stream as (17), the amount of specific heat needed to evaporate moisture from the fabric as (18), the total heat consumption as (19), the required heat energy with losses considered (η_B= 87%) and (η_h= 80%) as (20), fuel volume consumption per hour as (21), yearly fuel volume consumption as (22), the total yearly heat consumption (23), the total yearly heat consumption in tonne of coal equivalent (TCE) as (24).

3.3. Recuperative drying process with recuperator efficiency of η_R= 58%

Theoretical enthalpy of air leaving the recuperator is calculated as (25), real enthalpy of air leaving the recuperator as (26), real temperature of air leaving the recuperator as (27), the amount of specific heat needed to evaporate moisture from the fabric as (28), the total heat consumption as (29), the required heat energy with losses considered (η_B= 87% and η_h= 80%) as (30), fuel volume consumption per hour as (31), yearly fuel volume consumption as (32), the total yearly heat consumption as (33), and the total yearly heat consumption in tonne of coal equivalent (TCE) as (34).

3.4. Combined drying process utilizing both recirculation and recuperative heat recovery

Humidity ratio of air leaving the process (state 5) is calculated as (35), humidity ratio of air entering the stenter at state 4 as (36), enthalpy of air entering the stenter at state 4 as (37), temperature of air at mixing point between humid process and ambient air stream as (38), enthalpy of air at mixing point between humid process and ambient air stream as (39), the amount of specific heat needed to evaporate moisture from the fabric as (40), the total heat consumption as (41), the required heat energy with losses considered (η_B= 87% and η_h= 80%) as (42), fuel volume

$$D_{ZS}=D_Z\cdot(1-Y_O)=8450\cdot(1-0.53)=3971.5\text{ kg/h} \quad (12)$$

$$d_4=\left[(D_{H_2O}/D_{ZS})+d_1\right]=[(185.9/3971.5)+0.008]=0.055\text{ kg}_{H_2O}/\text{kg}_{\text{suhog zraka}} \quad (13)$$

$$d_2=\left[d_4-(D_{H_2O}/D_Z)\right]=[0.055-(185.9/8450)]=0.033\text{ kg}_{H_2O}/\text{kg}_{\text{suhog zraka}} \quad (14)$$

$$h_4=h_3=t_{a3}+(2500+1.96\cdot t_{a3})\cdot d_3=160+(2500+1.96\cdot 160)\cdot 0.033=252.85\text{ kJ/kg} \quad (15)$$

$$t_{a2}=(1-Y_O)\cdot t_{a1}+Y_O\cdot t_{a4}=(1-0.53)\cdot 25+0.53\cdot 100=64.75°\text{C} \quad (16)$$

$$h_2=t_{a2}+(2500+1.96\cdot t_{a2})\cdot d_2=64.75+(2500+1.96\cdot 64.75)\cdot 0.033=151.44\text{ kJ/kg} \quad (17)$$

$$q_t=(h_3-h_2)/(d_4-d_3)=(252.85-151.44)/(0.055-0.033)=4609.55\text{ kJ/kg}_{H_2O} \quad (18)$$

$$Q_t=D_{H_2O}\cdot q_t=185.9\cdot 34609.55=856\ 915.35\text{ kJ/h} \quad (19)$$

$$Q́_t=Q_t/(\eta_B\cdot\eta_h)=856\ 915.35/(0.87\cdot 0.8)=1\ 231\ 200.2\text{ kJ/h} \quad (20)$$

$$V_g=Q́_t/H_n=1\ 231\ 200.2/35649=34.5\text{ m}^3/\text{h} \quad (21)$$

$$V_{gg}=V_g\cdot\tau=34.5\cdot 1471.7=50\ 773.65\text{ m}^3/\text{godišnje} \quad (22)$$

$$Q_g=Q́_t\cdot\tau=1\ 231\ 200.2\cdot 1471.7=1.81\cdot 10^9\text{ kJ/godišnje} \quad (23)$$

$$Q_{tEU}=Q_g/29.3\cdot 10^6=1.81\cdot 10^9/29.3\cdot 10^6=61.84\text{ tEU} \quad (24)$$

$$h_{2a}=t_{z2a}+(2500+1.96\cdot t_{z2a})\cdot d_{2a}=100+(2500+1.96\cdot 100)\cdot 0.008=118.4\text{ kJ/kg} \quad (25)$$

$$h_2=\eta_R\cdot(h_{2a}-h_1)+h_1=0.58\cdot(118.4-45.4)+45.4=87.7\text{ kJ/kg} \quad (26)$$

$$t_{z2}=(h_2-2500\cdot d_2)/(1+1.96\cdot d_2)=(87.7-2500\cdot 0.008)/(1+1.96\cdot 0.008)=66.65°\text{C} \quad (27)$$

$$q_t=(h_3-h_2)/(d_4-d_2)=(182.5-87.7)/(0.03-0.008)=4309.1\text{ kJ/kg}_{H_2O} \quad (28)$$

$$Q_t=D_{H_2O}\cdot q_t=185.9\cdot 4309.1=801\ 061.7\text{ kJ/h} \quad (29)$$

$$Q́_t=Q_t/(\eta_B\cdot\eta_h)=801\ 061.7/(0.87\cdot 0.8)=1\ 150\ 950.7\text{ kJ/h} \quad (30)$$

$$V_g=Q́_t/H_n=1\ 150\ 950.7/35649=32.3\text{ m}^3/\text{h} \quad (31)$$

$$V_{gg}=V_g\cdot\tau=32.3\cdot 1471.7=47\ 535.9\text{ m}^3/\text{godišnje} \quad (32)$$

$$Q_g=Q́_t\cdot\tau=1\ 150\ 950.7\cdot 1471.7=1.69\cdot 10^9\text{ kJ/godišnje} \quad (33)$$

$$Q_{tEU}=Q_g/29.3\cdot 10^6=1.69\cdot 10^9/29.3\cdot 10^6=57.8\text{ tEU} \quad (34)$$

consumption per hour as (43), yearly fuel volume consumption as (44), the total yearly heat consumption as (45), and the total yearly heat consumption in tonne of coal equivalent (TCE) as (46).

$$d_5=\{[D_{H_2O}/(D_a\cdot(1-Y_O)]+d_1\}=\{[185.9/(8450\cdot(1-0.53)]+0.008\}=0.055\ kg_{H_2O}/kg_{dry\ air} \quad (35)$$

$$d_3=d_4=[d_5-(D_{H_2O}/D_a)]=[0.055-(185.9/8450)]=0.033\ kg_{H_2O}/kg_{dry\ air} \quad (36)$$

$$h_4=h_5=t_{a4}+(2500+1.96\cdot t_{a4})\cdot d_4=160+(2500+1.96\cdot 160)\cdot 0.033=252.85\ kJ/kg \quad (37)$$

$$t_{a3}=(1-Y_O)\cdot t_{a2}+Y_O\cdot t_{a5}=(1-0.53)\cdot 66.65+0.53\cdot 100=84.3°C \quad (38)$$

$$h_3=t_{a3}+(2500+1.96\cdot t_{a3})\cdot d_3=84.3+(2500+1.96\cdot 84.3)\cdot 0.033=172.55\ kJ/kg \quad (39)$$

$$q_t=(h_4-h_3)/(d_5-d_3)=(252.85-172.55)/(0.055-0.033)=3650\ kJ/kg_{H_2O} \quad (40)$$

$$Q_t=D_{H_2O}\cdot q_t=185.9\cdot 3650=678\ 535\ kJ/h \quad (41)$$

$$\acute{Q}_t=Q_t/(\eta_B\cdot\eta_h)=678\ 535/(0.87\cdot 0.8)=974\ 906.6\ kJ/h \quad (42)$$

$$V_g=\acute{Q}_t/H_n=974\ 906.6/35649=27.35\ m^3/h \quad (43)$$

$$V_{gg}=V_g\cdot\tau=46.7\cdot 1471.7=40\ 251\ m^3/year \quad (44)$$

$$Q_g=\acute{Q}_t\cdot\tau=974\ 906.6\cdot 1471.7=1.44\cdot 10^9\ kJ/year \quad (45)$$

$$Q_{TCE}=Q_g/29.3\cdot 10^6=1.44\cdot 10^9/29.3\cdot 10^6=48.97\approx 49\ TCE \quad (46)$$

4. Results

The calculated fuel savings become 26.06% with recirculative, 30.86% with recuperative and 41.39% with combined process while the yearly heat consumption is lowered from $83.6\cdot 10^9$ tEU in basic process to $61.8\cdot 10^9$ tEU in recirculating drying process. Recuperative drying process shows heat savings in amount of $57.8\cdot 10^9$ tEU and the most significant heat savings are seen using combined process ($49\cdot 10^9$ tEU).
As calculated in the paper, yearly fuel consumption is lowered from $6.87\cdot 10^4$ m^3 in basic process to as much as $4.03\cdot 10^4$ m^3 in combined heating process utilizing both recirculation and recuperative heat recovery as seen in Table 1.

Tab.1 Yearly volume and heat savings in stenter system with indirect heating systems

Process	Yearly fuel volume consumption (m^3)	Yearly fuel savings (%)	Yearly heat consumption (tEU)	Ušteda toplinske energije godišnje (%)
simple	$6.87\cdot 10^4$		$83.6\cdot 10^9$	-
recirculating	$5.08\cdot 10^4$	26.06	$61.8\cdot 10^9$	26,08
regenerating	$4.75\cdot 10^4$	30.86	$57.8\cdot 10^9$	30,86
combined	$4.03\cdot 10^4$	41.34	$49\cdot 10^9$	41,39

5. Conclusion

Optimization of the drying process by applying exhaust air recovery can results in significant energy savings. By applying exhaust air for preheating purposes using recuperative and recirculative options, or combination of both, reduces the amount of fuel needed to heat the air in fabric stenters. The comparison between real, recirculative, recuperative and combined processes, as well as indirect and direct heating systems, shows fuel savings. Fuel savings with indirect heating system show fuel savings over the real process of 26.06% with recirculative, 30.86% with recuperative and 41.39% with combined process.

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