Waste Heat and Wastewater Recovery in Textile Processing Industry: A Case Study of Adopted Practices

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ABSTRACT

Textile wet processes dispose of huge amounts of water and energy in the form of hot wastewater and exhaust gas emissions. A significant amount of water and energy can be conserved by adopting various waste heat and water recovery methods, such as the use of heat exchanger, recycling hot wastewater, steam condensate, and cooling water recovery and reuse. In this study, various waste energy and water conservation methods are summarized to highlight their importance for water and energy conservation. For practical consideration, a detailed assessment of such practiced methods was done in one textile processing industry. The obtained results revealed that a high amount of energy and water could be conserved by adopting various waste heat and water recovery methods, with the advantage of reducing environmental pollution while minimizing the consumption of energy and water.

Keywords: Waste Heat Recovery, Textile Wastewater, Wastewater Treatment and Reuse.

1. INTRODUCTION

Waste heat is resulted from a process of fuel combustion, chemical reaction, and hot liquid process and discharged in the environment in the form of exhaust emission and hot wastewater without being recovered for practical application [1, 2]. The recovery and usage of waste heat require needless efforts to modify the conventional industrial processes or machinery, to cut process costs and further to control environment pollution. For the intended use and for value addition in textile products, various wet processes are carried out, such as bleaching, mercerizing [3], dyeing, printing, washing, and finishing [4, 5]. All these processes are energy and water-intensive and consume a huge amount of energy and water [6-8]. Water is used as a transport medium to perform wet processes, while energy is needed for process heating, either in the form of saturated steam or in the form of hot air, to increase the kinetics of the mentioned processes. During these processes, a huge amount of waste heat and hot wastewater is generated and discharged into the waste streams, that could be reutilized with an adaptation of various cleaner production practices such as the use of waste heat exchangers at process outlet to recover heat for heating the freshwater [9, 10].

In the textile wet processing industry, the main source of energy input/fuel is the combustion of natural gas for the generation of electricity, saturated steam

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production, to perform drying and curing processes [11]. The electricity provides power to operate the machines, and saturated steam is used for process water heating, fabric steaming and for dryers heating. Considering the main focus on the production, the waste streams of these processes often neglected, without pondering their significance in recovering energy and water from such streams. In brief, the main sources of such waste heat energy and hot wastewater are [6]:

- Exhaust emissions from the chimneys of steam boilers, power turbines, and generators, drying and curing processes.
- Hot wastewater discharged from textile processes and washing baths.
- Water used for cooling (cooling water) of power generators, radiators, process equipment, cooling cylinders, and other plants, as their cooling is necessary for continuous operations.
- Steam condensate resulted after condensation of saturated steam i.e. when the latent heat of steam is utilized and condensed into pure hot water.

It is estimated that approximately half of the total industrial energy consumption is discharged as waste heat. However, implementation of simple modification at disposal streams could help in recovering and reusing this waste heat without affecting any process or quality of the product [12]. In addition, such implementations are considered cleaner production practices in textile processing [13]. Moreover, the consideration of these practices is now becoming necessary, because of the significance of energy and water conservation, due to scarcity and insufficiency to fulfill future demands [14, 15]. Furthermore, increased energy cost and high industrial competition have highlighted the importance of adopting efficient energy and water management in the industrial processes [16], along with are useful to reduce environmental pollution [17, 18].

In this work, different waste streams of the textile processing industry are discussed in detail in terms of the type and temperature of each stream. Moreover, various Waste Heat Recovery (WHR) methods are overviewed in detail. Besides, to show the practical viability of such methods and resulted in advantages i.e. the recovered amount of wasted energy and water, assessment of applied WHR methods and environmental management practices was done in one of the leading textile mills in Pakistan. Such assessment includes continuous monitoring of the cooling water, steam condensate, on-site water reuse, heat exchangers and exhaust emissions to estimate and calculate the amount of recovered energy and reused wastewater, with the adoption of WHR methods.

2. OVERVIEW OF THE RECOVERY METHODS

2.1 Water and Energy Recovery

In textile wet processing, water is the main input to perform bleaching, mercerizing, dyeing, printing, washing, and finishing processes [19]. Moreover, water is used for saturated steam production and cooling of electric generators and hot equipment. For the mentioned processes, hot water is needed, i.e. up to 80-90 °C, which after the application is directly disposed of as hot wastewater. To reduce the waste generation at the source the best approach is the on-site reuse of the hot wastewater within a similar application [20, 21]. This could be achieved with collection and screen filtration of the hot wastewater from one stage of the process and its reuse in the other stage of the same process, as shown in Fig. 1. By adopting this method, both water and energy could be recovered, and their consumption could be reduced. While waste energy of the disposed of hot wastewater could be further recovered by employing a heat exchanger at the final outlet, through which the incoming fresh feed-water is brought in indirect contact to allow heat transfer between hot wastewater and fresh feed-water as shown in Fig. 1.

2.1.1 Cooling Water Heat Recovery

Cooling of equipment and plants is a common industrial practice, in which cooling water is used to retreat heat from certain equipment through conduction, for their smooth performance and continuous operation [22]. In common practice, the heat of cooling water is wasted at cooling towers and brought back in cooling operation under a closed cyclic system, as shown in the scheme in Fig. 2.

Mehran University Research Journal of Engineering and Technology, Vol. 40, No. 3, July 2021 [p-ISSN: 0254-7821, e-ISSN: 2413-7219]
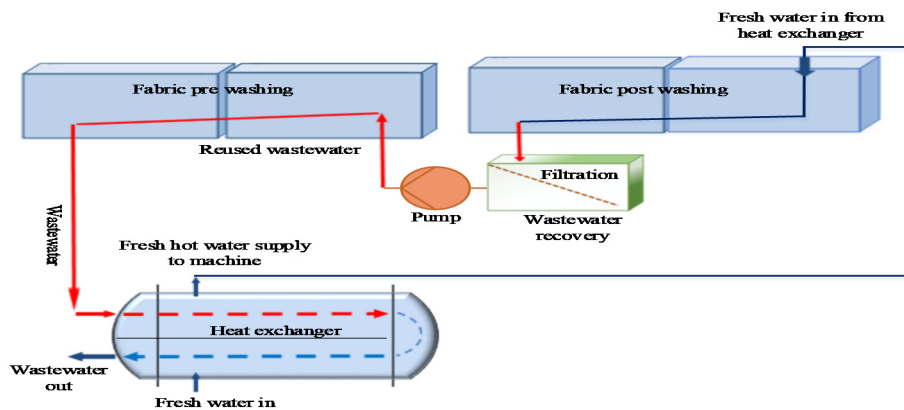
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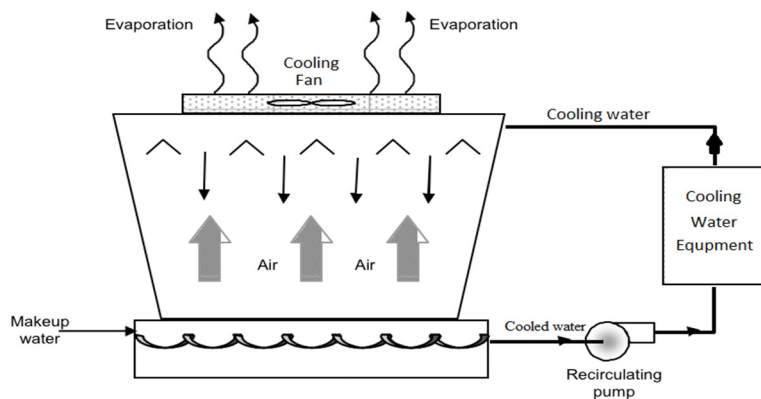Fig. 1: Water recycling and on-site water reuse at the wet-processing machine with water heat exchanger
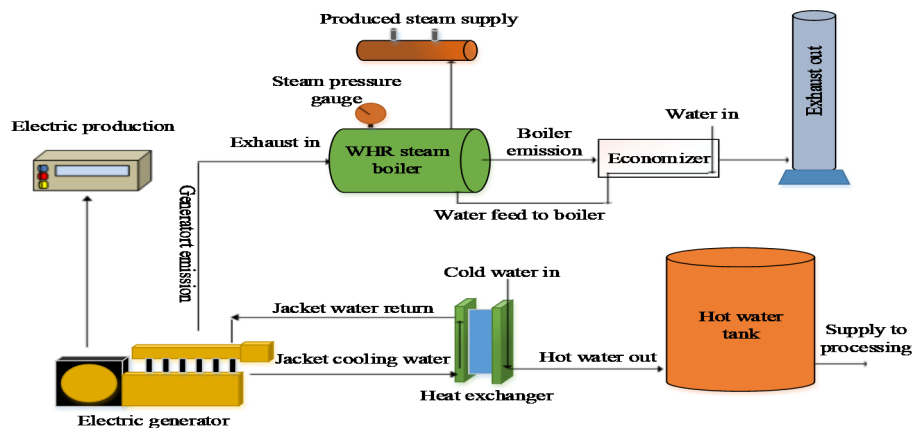

Fig. 2. Schematic diagram of cooling tower

Fig. 3: Cooling water heat recovery from electric generator jacket water, with steam generation from Whr Boiler and Economizer.

However, the heat in cooling water could be recovered with the use of heat exchanger to heat the fresh water before supply to process or machines, as shown in the scheme in Fig. 3 showing the method of heat exchange between cooling water of power generator and process freshwater.

2.1.2 Steam Condensate Recovery

A steam boiler produces saturated steam, which is mainly used for heating process water. The produced statured steam is either directly injected or indirectly utilized by passing the steam inside a plate or tubes (to

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heat the surrounded process water) [23]. The difference in both types is shown in Fig. 4(a-b). During indirect usage, the latent heat is utilized, and steam is condensed into freshwater commonly termed as hot steam condensate. This steam condensate being hot and pure water is the important source of steam boiler feed-water. Therefore it is recovered from various processes through steam condensate return lines and further supplied to the steam boilers feed-water system, as shown in Fig. 5. Most of the washing baths/chambers and steam dryers are heated using indirect methods and generate a significant amount of condensate.
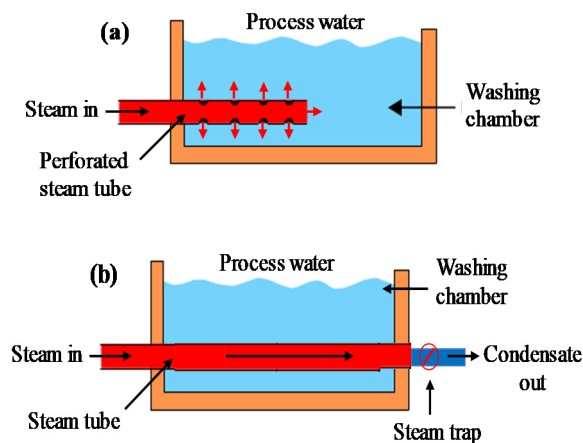

Fig. 4: Types of steam usage: (a) Direct steam use, and (b) Indirect steam use.
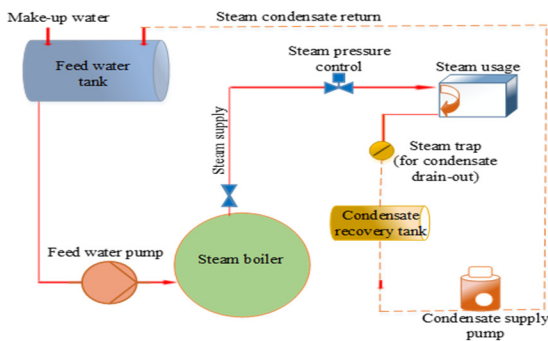

Fig. 5: Schematic diagram of steam condensate recovery

2.2 Heat Recovery from Exhaust Emissions

The main sources of waste heat from industries include exhaust emissions from power plants, steam boilers, and other curing machines. The average heat efficiency of the conventional power plant is around 35 - 40% [24], while the remaining energy is lost into the environment, in the form of exhaust emissions, and conduction and radiation losses [25]. The combustion of power turbine, power generator, and steam boilers released high amount of exhaust heat i.e. in the ranges 250–580 ºC, therefore recovered heat from such streams have significance. Some of the adopted WHR methods on such exhaust streams are discussed in upcoming sections.

2.2.1 Waste Heat Recovery Boilers

The exhaust emissions could be used for the production of saturated steam by employing the waste heat recovery boiler, also termed as a smoke tube steam boiler, already in practice for various applications [26, 27]. Generally, a smoke tube WHR boiler contains a web of parallel tubes, and inside these, the exhaust gasses are passed. Initially, the water is heated (outside the tubes), and then water vapor is pressurized for the production of saturated steam. Such a smoke tube boiler can be placed at the exhaust outlet of power generator or turbines, as shown in the scheme in Fig. 3.

2.2.2 Economizers

The steam boiler running on natural gas (CH_4)/fuel produced exhaust emissions of the medium temperature range (180 - 265 ºC) [28]. For recovery of waste heat from the emissions of a steam boiler, an economizer could be employed at a boiler outlet for exchanging its contribution to the incoming boiler feed-water [29], as shown in the scheme given in Fig. 3. This economizer has the same working principle as of heat exchanger (discussed earlier), but the exhaust heat source is in the gas phase [30]. By adopting this practice, the thermal efficiency of the steam boiler could be improved along with the reduction of boiler fuel consumption.

3. EXPERIMENTAL ASSESSMENT

To summarize the practical viability of earlier discussed WHR methods, a detailed assessment was made at Yunus Textile Mills (YTM), Pakistan, where it is known as the largest exporter of textile goods made in the country. YTM has a production and processing capacity of 100 million meters of textile fabric per year. YTM is equipped with continuous

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textile wet processing machines (machines details and processes layouts are given in Fig. 6) and has its power plant for electricity generation and steam boilers for saturated steam production. Details of the power and steam generation equipment, textile wet processing machines, and perform processes in YTM are given in Table 1-2. Most of the WHR methods discussed in earlier sections are adopted by YTM, the summarized information, including the sources of generated waste heat, wastewater, and adopted WHR method along with environmental benefits associated to each recovery method, is given in Table 3.

The analyses of recovered waste heat and water from the adopted methods were made by (i) thermal assessment of the amount of energy recovered/transferred from wastewater with monitoring temperature changes at the inlets and outlets of WHR equipment i.e. heat exchanger, economizer etc., (ii) quantitative assessment of the amount of the water and steam after monitoring and analysis of their consumption from mounted flow meters at the water and steam lines and (iii) quantitative assessment of the steam condensate recovery after monitoring and analyzing the amount of recovered condensate from the mounted flow meter at condensate return lines.
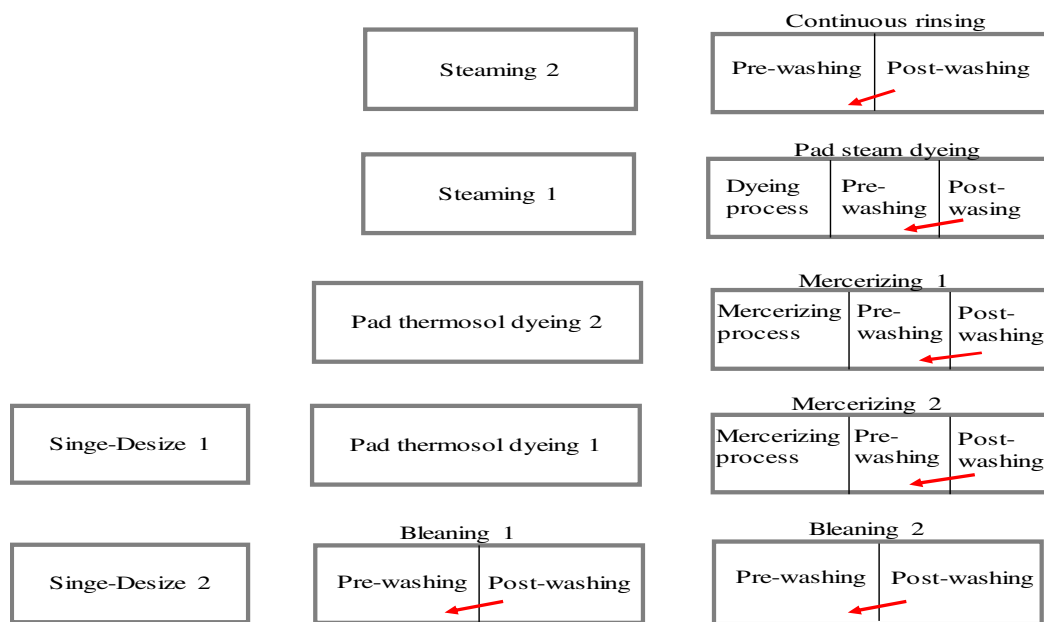

Fig. 6: Textile Wet-Processing machines and processes layout at Yunus Textile Mills. Red arrows are related to the heat flux and hot wastewater flow.

Table 1: Details of YTM power and steam generation equipments				
Details	Quantity	Made	Purpose	Production capacity
Gas power turbine	2	Solar Caterpillar	Power generation	1 MW each
Engine 3516C	1	Caterpillar	Power generation	1.4 MW
Engine 3516A	1	Caterpillar	Power generation	1 MW
Gas boiler 1	1	Descon	Steam generation	10 ton h^{-1}
Gas boiler 2	1	DDFC	Steam generation	7 ton h^{-1}
WHR smoke tube boiler 1	1	DDFC	Steam generation	8 ton h^{-1}
WHR smoke tube boiler 2	1	DDFC	Steam generation	1.2 ton h^{-1}
CRP	1	Korting Hannover AG	Caustic soda recovery after mercerize process	1.4 m^3 h^{-1}
MW = megawatt, WHR = waste heat recovery, CRP = caustic recovery plant				

Table 2: Details of YTM Wet-Processing Machines.				
Details	Quantity	Made by	Purpose	Production capacity (10^3 m d^{-1})
Singe-desize	2	Osthoff	Singing: the direct burning flame is used for fabric surface treatment Desizing: enzymes are used for the removal of starch	260
Bleaching	2	Goller	Initial treatment of textile fabric for the removal of natural and artificial impurities	250
Mercerize	1	Goller	Textile Treatment with caustic to improve fabric absorbency	75
Pad steam dyeing	1	Goller	Dyeing and coloring of fabric	65
Pad thermosol dyeing	2	Monforts	Dyeing and coloring of fabric	80
Continuous rinsing	1	Kuster	Textile fabric washing after dyeing and printing	70
Steaming	2	Arioli/salvade	Steam treatment of printed fabric to fix color	140

Table 3: Details of YTM heat recovery sources and WHR methods with environmental and economic advantages		
Machine/source of heat energy	WHR method	Potential advantages
Cooling water from singe-desize burners, cooling cylinders, power engine, and caustic recovery plant	Cooling water collection and supply to rinsing and washing processes	Conservation of water and energy. Resource sustainability due to reduced emission and low steam consumption.
The heat from wastewater after bleaching, mercerize, pad steam dyeing, and continuous rinsing	Heat transfer from discharged wastewater to increase the temperature of fresh process water	Conservation of energy and low temperature of final discharged water reduced oxygen depletion
Bleaching and mercerize machines post washing water recovery and reuse	Post washing processes water recovery and reuses in pre-washing	Conservation of water and steam.
Steam condensate generated from heating baths and various processes	Recovery and supply to the steam boiler feed-water system.	Conservation of water and energy. Low fuel consumption for steam production.
Exhaust emissions generated by two power turbines and generators	Exhaust emission of turbines and generators are used for steam generation or heating process water	Conservation of energy. Low temperature and reduced exhaust emissions
Two gas fuel steam boilers and two smoke tube WHR steam boilers	Pre-heated feed-water supply by means of heat transfer from exhaust emissions of the steam boiler	Low fuel consumption by avoiding excess water heating. Increase in boiler efficiency

Before monitoring and analyzing each source, the monitoring instruments, i.e. temperature gauges, flowmeters of steam, water, and condensate, were calibrated. The frequency of the monitored data was twice a day and remained to continue up to 60 days duration. For the final assessment, an average of recorded temperatures and flows was considered. The amount of recovered/transferred heat was determined by taking the difference of the inlets and outlet temperatures that were applied in equation (1), along with the recorded average quantity of water, to calculate the amount of effective recovered energy.

$$Q = mC_p\Delta T \qquad (1)$$

where Q is the heat energy in kJ, m is mass or quantity or amount in kg or L, C_p is the specific heat of the water 4.184 kJ kg^{-1} °C^{-1}, and ΔT is the temperature

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difference in °C. The obtained values in kJ were converted in Millions British Thermal Unit (MBTU), by dividing the obtained values by 1.055×10^5.

4. RESULTS AND DISCUSSION

4.1 Cooling Water Recovery

Table 4 shows the amount of recovered cooling water and energy from different sources, which were calculated from the recorded average temperatures and quantities. The recovered amount of cooling water and heat was low, from cooling cylinders of processing machines because these processes need less amount of water and retreated heat is also low due to continuous cooling water flow. While in the case of cooling of the power generator and caustic recover plant (CRP) condenser, where the retreated heat and amount of recovered cooling water were higher.

4.2 Heat Exchangers

Table 5 shows the amount of recovered heat (for heating the freshwater) with the use of heat exchangers at various sources. The heat gain (ΔT) from shell and tube type heat exchanger (shown in Fig. 1) was in the range of 18-25 °C, but for plate type heat exchanger (located at one of the continuous rinsing machines) the heat gain was higher, as it allowed good contact of

inlet freshwater with exited hot wastewater, therefore, resulted in higher heat transfer than shell and tube type heat exchanger. The recovered amount of heat from wastewater revealed that significant energy is being recovered in heating inlet freshwater, which eventually reduced the excess use of saturated steam.

4.3 On-Site Water Reuse

Assessment of on-site water reuse was made at two bleachings, and one mercerize machines, where the collected water after final-washing stages were recovered and reused in pre-washing stages (refer Fig. 1). The analysis was done by taking the temperature difference of reused water, and freshwater and the recorded amount of reused water, and the calculated amounts are given in Table 6. The quantity of reused water of bleaching-1 machine was higher than bleaching-2 and mercerize machines, because of its higher textile processing capacity and high amount of generated wastewater.

4.4 Steam Condensate Recovery

Energy and water recovery from steam condensate were assessed by analyzing the average temperature and quantities of recovered steam condensate from various indirect steam usage sources, including two

Table 4: Assessment of recovered heat energy from cooling water					
Energy source/machine	Freshwater m³ d⁻¹	Freshwater °C			MMBTU year⁻¹
		In	Out	ΔT	
Singe-desize 1	60.5	20.0	39.5	19.5	1,685.2
Singe-desize 2	60.0	20.2	39.0	18.8	1,611.2
Pad thermosol dyeing 1	29.5	20.5	40.3	19.8	834.3
Pad thermosol dyeing 2	30.5	20.3	39.8	19.5	849.5
Power generator jacket	220.8	21.0	75.2	54.2	17,094.2
CRP condenser	312.2	21.5	70.1	48.6	21,673.0
Total	713.5				43,747.4

Table 5: Assessment of recovered heat energy from heat exchangers					
Energy source/machine	Freshwater m³ d⁻¹	Freshwater °C			MMBTU year⁻¹
		In	Out	ΔT	
Bleaching 1	280.1	20.2	40.5	20.3	8,121.3
Bleaching 2	180.0	21.0	39.2	18.2	4,679.4
Mercerize 2	139.9	20.5	42.8	22.3	4,456.9
Pad steam dyeing	146.2	20.7	45.5	24.8	5,186.1
Continuous rinsing	148.8	20.0	55.1	35.1	7,460.4
Total	895.2				29,904.1

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Table 6: Assessment of recovered heat energy from On-Site water reuse					
Energy source/machine	Reused water m³ d⁻¹	Freshwater ºC	Reused water ºC	ΔT ºC	MMBTU year⁻¹
Bleaching 1	100.8	20.7	81.4	60.7	8,739.7
Bleaching 2	40.8	21.2	78.9	57.7	3,362.7
Mercerize 2	36.0	20.1	75.3	55.2	2,838.5
Total	177.6				14,940.9

bleachings, mercerize, pad steam dyeing, continuous rinse, and two steaming machines. The recovered energy from steam condensate is given in Table 7, which was calculated after taking the difference of the steam condensate and the average temperature of fresh boiler make-up water. In YTM, average steam consumption was 505 ton d⁻¹ and steam condensate recovery from all sources is about 56.7% of the total steam consumption because some of the processes in YTM utilized direct injection of steam for process heating i.e. at steamers of bleaching, washing baths, and pad steam dyeing machines. The total amount of saved water through the recovery of reused water (Table 6) and steam condensate (Table 7) was about 167,076 m³ year⁻¹.

4.5 Heat Recovery from Exhaust Emission

For the assessment of the exhaust emissions released from steam boilers, electric generators, and turbines, the temperature of emissions (released after combustion operation) were recorded from each source at the inlet and outlet of the employed economizers and WHR smoke-tube steam boilers. Amount of recovered heats are given in Tables 8-9, calculated from the produced saturated steam from smoke-tube WHR boilers and pre-heating of the boiler feed-water through economizer. Steam production and economizer pre-heating of smoke-tube WHR boiler-1 were higher than boiler-2 i.e. around 518 ºC and flow of generated emissions were higher from two power turbines, compared to one power generator emissions applied at smoke-tube WHR boiler 2. While recovered heat from the economizer at gas fuel boiler-1 was higher than gas boiler-2, due to its higher capacity of steam production (10 ton h⁻¹) and temperature of released emissions at the economizer inlet, as observed in the given Table 9.

Table 7: Assessment of recovered heat energy from steam condensate					
Energy source/machine	Condensate (m³ d⁻¹)	Condensate ºC	Make-up water ºC	ΔT ºC	MMBTU (year⁻¹)
Bleaching 1	102.6	99.5	20.4	79.1	11,592.4
Bleaching 2	45.9	98.8	20.3	78.5	5,146.7
Mercerize 2	54.5	97.5	20.5	77.0	5,994.3
Pad steam dyeing	46.9	99.2	20.1	79.1	5,299.1
Continuous rinsing	21.6	98.1	20.4	77.7	2,397.3
Steaming 1	7.8	97.6	20.2	77.4	862.4
Steaming 2	7.2	98.6	20.4	78.5	807.3
Total	286.5				32,099.4

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Table 8: Assessment of recovered heat energy from WHR boilers.				
WHR boilers	Exhaust emission ºC		Steam ton d⁻¹	MMBTU year⁻¹
	Inlet	Outlet		
Smoke-tube WHR boiler 1 (at exhaust outlet of two power Turbines)	518.2	265.1	189.6	134,338.2
Smoke-tube WHR boiler 2 (at exhaust outlet of power generator)	480.5	182.2	24.5	17,344.9
Total			214.1	151,683.1
At 5 bar gauge pressure, 1 kg of steam has 2.0764 MJ energy in the form of heat enthalpy. Conversion 1 MMBTU = 1055 MJ				

Economizers	Boiler emission ºC		Feed-water m³ d⁻¹	Feed-water ºC			MMBTU year⁻¹
	In	Out		In	Out	ΔT	
Gas boiler 1	235.2	160.1	237.6	98.5	121.4	22.9	7,772.0
Gas boiler 2	180.1	131.2	50.4	98.3	113.1	14.8	1,065.5
Smoke-tube WHR boiler 1	265.1	155.4	192.2	98.4	140.2	41.8	11,478.1
Smoke-tube WHR boiler 2	182.2	136.3	25.2	98.5	108.3	9.78	352.0
Total			505.4				20,667.6

Table 9: Assessment of recovered heat energy from boiler economizers

YTM uses natural gas (CH_4) as fuel, and the estimated saving of CH_4 was around 293,043 MMBTU year⁻¹. According to US EPA, the CO_2 emissions coefficient is 53.1 Kg CO_2 per MMBTU of CH_4 [31]. Therefore, the overall associated environmental benefits in terms of CO_2 reduction was around 15,561 ton year⁻¹.

5. CONCLUSIONS

In the textile wet processing industry, a huge amount of wasted energy and water could be conserved by implementing various WHR methods that could reduce the fuel consumption in heating the process water and for steam production and eventually could reduce environmental pollution by minimizing the emissions level. The use of heat exchanger at outlets of the textile process and stacks of the power turbines and boilers could decrease the temperature of the waste streams i.e. wastewater and exhaust emissions. The performed assessment of adopted WHR methods at YTM confirmed the suitability and practicability of such methods for energy recovery from reused water, cooling water, steam condensate, wastewater and exhaust emissions of steam boilers and power plant. Estimated water conservation through water reuse and steam condensate recovery was around 167,076 m³ year⁻¹. YTM uses CH_4 as a fuel, and an overall estimated saving of methane was around 293,043 MMBTU year⁻¹ and estimated CO_2 reduction was around 15,561 ton year⁻¹, with the utilization of various WHR methods i.e. use of cooling water, steam condensate, heat exchangers, reuse of hot wastewater and exhaust emissions.

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REFERENCES

1. Nwosu P., "Condenser-side integration of a simple solar-type waste heat recovery device in a thermal plant", *Journal of Cleaner Production,* Vol. 157, pp. 333-341, 2017.

2. Kapil A., Bulatov I., Smith R., Kim J.-K., "Site-wide low-grade heat recovery with a new cogeneration targeting method", *Chemical Engineering Research and Design,* Vol. 90, no. 5, pp. 677-689, 2012.

3. Zahid B., Faisal S., Siddique H., "Analysis of Caustic Soda of Different Manufacturers in Pakistan for Mercerization of Cotton Textiles", *Mehran University Research Journal of Engineering and Technology*, Vol. 36, No. 4, pp. 857-866, October 2017.

4. Ali I., Kim S.-R., Kim S.-P., Kim J.-O., "Recycling of textile wastewater with a membrane bioreactor and reverse osmosis plant for sustainable and cleaner production", *Desalination and Water Treatment,* pp. 1-9, 2016.

5. Baydar G., Ciliz N., Mammadov A., "Life cycle assessment of cotton textile products in Turkey", *Resources, Conservation and Recycling,* Vol. 104, pp. 213-223, 2015.

6. Rakib M. I., Saidur R., Mohamad E. N. A., Afifi M., "Waste-heat utilization–the sustainable technologies to minimize energy consumption in

Mehran University Research Journal of Engineering and Technology, Vol. 40, No. 3, July 2021 [p-ISSN: 0254-7821, e-ISSN: 2413-7219]

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Bangladesh textile sector", *Journal of Cleaner production,* Vol. 142, pp. 1867-1876, 2017.

7. Mokhtar N., Lau W., Ismail A., Kartohardjono S., Lai S., Teoh H., "The potential of direct contact membrane distillation for industrial textile wastewater treatment using PVDF-Cloisite 15A nanocomposite membrane", *Chemical Engineering Research and Design,* Vol. 111, pp. 284-293, 2016.

8. Qureshi R. F., Qureshi K., Bhatti I., Khatri Z., "Statistical modeling for stability of emulsion liquid membrane for the removal of anionic dyes from textile wastewater", *Mehran University Research Journal of Engineering and Technology,* Vol. 37, no. 3, p. 631, 2018.

9. Erdumlu N., Ozipek B., Yilmaz G., Topatan Z., "Reuse of effluent water obtained in different textile finishing processes", *AUTEX Research Journal,* Vol. 12, no. 1, pp. 23-28, 2012.

10. Ozturk E., Koseoglu H., Karaboyacı M., Yigit N. O., Yetis U., Kitis M., "Minimization of water and chemical use in a cotton/polyester fabric dyeing textile mill", *Journal of Cleaner Production,* Vol. 130, pp. 92-102, 2016.

11. Sharma S., "Energy management in textile industry"m *International Journal of Power System Operation and Energy Management*, Vol. 2, No. 1, pp. 2, 2012.

12. Oğulata R.T., "Utilization of waste-heat recovery in textile drying", *Applied Energy,* Vol. 79, No. 1, pp. 41-49, 2004.

13. Ozturk E., Koseoglu H., Karaboyaci M., Yigit N. O., Yetis U., Kitis M., "Sustainable textile production: cleaner production assessment/eco-efficiency analysis study in a textile mill", *Journal of Cleaner Production,* Vol. 138, pp. 248-263, 2016.

14. Ersayin E., Ozgener L., "Performance analysis of combined cycle power plants: A case study", *Renewable and Sustainable Energy Reviews,* Vol. 43, pp. 832-842, 2015.

15. Breach P. A., Simonovic S. P., "Wastewater Treatment Energy Recovery Potential For Adaptation To Global Change: An Integrated Assessment", *Environmental Management,* Vol. 61, No. 4, pp. 624-636, 2018.

16. Vajnhandl S., Valh J. V., "The status of water reuse in European textile sector," *Journal of Environmental Management,* Vol. 141, pp. 29-35, 2014.

17. Hatami M., Ganji D., Gorji-Bandpy M., "A review of different heat exchangers designs for increasing the diesel exhaust waste heat recovery", *Renewable and Sustainable Energy Reviews,* Vol. 37, pp. 168-181, 2014.

18. Wu J.-G., Meng X.-Y., Liu X.-M., Liu X.-W., Zheng Z.-X., Xu D.-Q., Sheng G.-P., Yu H.-Q., "Life cycle assessment of a wastewater treatment plant focused on material and energy flows", *Environmental Management,* Vol. 46, No. 4, pp. 610-617, 2010.

19. Hussain T., Wahab A., "A critical review of the current water conservation practices in textile wet processing", *Journal of Cleaner Production,* Vol. 198, p,p. 806-819, 2018.

20. Elahee K., "Heat recovery in the textile dyeing and finishing industry: lessons from developing economies," *Journal of Energy in South Africa,* Vol. 21, pp. 9-15, 2010.

21. Ulson S. M. d. A. G., Melo A. R., de Souza A. A. U., "Re-utilisation conditions of wastewaters from textiles industries", *Resources, Conservation and Recycling,* Vol. 49, No. 1, pp. 1-13, 2006.

22. Shaikh M. A., "Water conservation in textile industry", *Pakistan Textile Journal,* Vol. 58, No. 11, pp. 48-51, 2009.

23. Alanya S., Ozturk E., Morova F., Yetis U., Dilek F., Demirer G., "Environmental performance evaluation of textile wet processing sector in Turkey", *Proceedings of the 9th Annual EMAN Conference*, Vienna, March 2006.

24. Vatopoulos K., Andrews D., Carlsson J., Papaioannou I., Zubi G., "Study on the state of play of energy efficiency of heat and electricity production technologies", *European Commission–JRC Scientific and Policy Reports, Petten, The Netherlands,* 2012.

25. Subramanyam S., "Utilization of the waste heat from internal combustion engines," *Resources, Conservation and Recycling,* Vol. 2, No. 4, pp. 297-304, 1989.

26. Jouhara H., Khordehgah N., Almahmoud S., Delpech B., Chauhan A., Tassou S. A., "Waste heat recovery technologies and applications", *Thermal Science and Engineering Progress,* Vol.

Mehran University Research Journal of Engineering and Technology, Vol. 40, No. 3, July 2021 [p-ISSN: 0254-7821, e-ISSN: 2413-7219]

615

6, pp. 268-289, 2018.

27. Haidar J. G., Ghojel J. I., "Waste heat recovery from the exhaust of low-power diesel engine using thermoelectric generators", *Proceedings of the 20th* IEEE *International Conference on Thermoelectrics, Beijing, China,* pp. 413-418, 8-11 June 2001.

28. Barma M., Saidur R., Rahman S., Allouhi A., Akash B., Sait S. M., "A review on boilers energy use, energy savings, and emissions reductions", *Renewable and Sustainable Energy Reviews,* Vol. 79, pp. 970-983, 2017.

29. Martelli E., Kreutz T. G., Gatti M., Chiesa P., Consonni S., "Numerical optimization of steam cycles and steam generators designs for coal to FT

plants," *Chemical Engineering Research and Design,* Vol. 91, No. 8, pp. 1467-1482, 2013.

30. Wang C., He B., Sun S., Wu Y., Yan N., Yan L., Pei X.", Application of a low pressure economizer for waste heat recovery from the exhaust flue gas in a 600 MW power plant", *Energy,* Vol. 48, No. 1, pp. 196-202, 2012.

31. U.S. Energy Information Administration, Carbon Dioxide Emissions Coefficients 2016. Available at http://www.eia.gov/environment/emissions/co2_vol_mass.cfm [Last accessed on August 14, 2020].

Mehran University Research Journal of Engineering and Technology, Vol. 40, No. 3, July 2021 [p-ISSN: 0254-7821, e-ISSN: 2413-7219]

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