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ENERGY EFFICIENCY OF LOUNDRY FACILITIES

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ABSTRACT

Services for washing and disinfecting linen and clothes in the modern world are especially popular in other large public enterprises such as hospitals, hostels, hotels, this explains the consolidation of laundries and their reorientation to large volumes of linen. Without a doubt, the laundry process on an industrial scale is a rather costly process. The factor that has a key influence on the cost of production of 1 kilogram of clean dry laundry: the energy (thermal, mechanical and electrical) spent on its production. Since the washing process takes place at high temperatures, it is obvious that heat losses in the washing cycle are quite large and at the moment these losses are simply wasted in enterprises, thereby losing energy, which can potentially bring income, as well as create problems for the environment.

In this thesis, a prototype of a highly automated production system is presented, the production process of an enterprise is described, using the simulation of the presented option to calculate the energy efficiency of some production cycles. The aim of the work is to compare several options for systems of energy efficiency systems for washing cycles.

Keywords: energy efficiency, laundries, heat exchangers

1 CONTENTS

1. INTRODUCTION

First of all, let us define the concept of energy efficiency. Energy efficiency is the process of reducing energy costs for a particular process with a constant result. That is, the optimization of the energy use process. The topic of energy efficiency is especially relevant in the modern world, as in recent years there has been a clear trend of conscious consumption to reduce environmental damage. Another important aspect in the topic of energy efficiency is the fact that a more energy efficient system reduces the financial cost of operating the system. /1/

At first glance, it may seem that energy efficiency is a kind of “reduction” of something, that is, less use, some kind of restriction, but the approach to this issue is not always so unambiguous, since one of the main tools for energy efficiency is reuse. For example, reuse of water in washing cycles. This helps to save resources and create a more favorable ecological environment. /1/

Laundry enterprises in the Russian Federation are a particularly promising area, since Russia has cheap energy resources. On the one hand, it may seem that this contributes to a faster development of the direction, however, if you study this issue in more detail, the situation is no longer so unambiguous, since our European colleagues strive to optimize their production as much as possible in order to reduce energy costs (as it is quite expensive compared to Russia) as a result, more energy efficient systems are being created in European countries. Another important factor for optimizing energy consumption is the reduction of carbon dioxide emissions and reduction of thermal pollution, which has a positive effect on the environment. However, the Russian market does not stand still and the need for optimization of laundry production is more and more clearly visible on it. /2/

2. ANALYSIS OF THE EXISTING ENTERPRISE

The basis of this study is a comparison of a real-life system in a laundry facility and its comparison with the same system when several energy efficiency solutions have been introduced into it. In this section of the work, an analysis of the processes taking place in production and analysis of them from an engineering point of view will be carried out in order to identify the most favorable places for optimizing energy efficiency. /1/

2.1. Analysis of enterprise processes

To optimize the washing cycle of laundry, it is necessary to consider the typical parts that make up the process of preparing clean laundry.

Dirty linen arrives at the laundry facility, sorted for easier washing and transported to the washing machines. /3/

Next, the process of preparing clean linen takes place, it is presented in Figure 1.

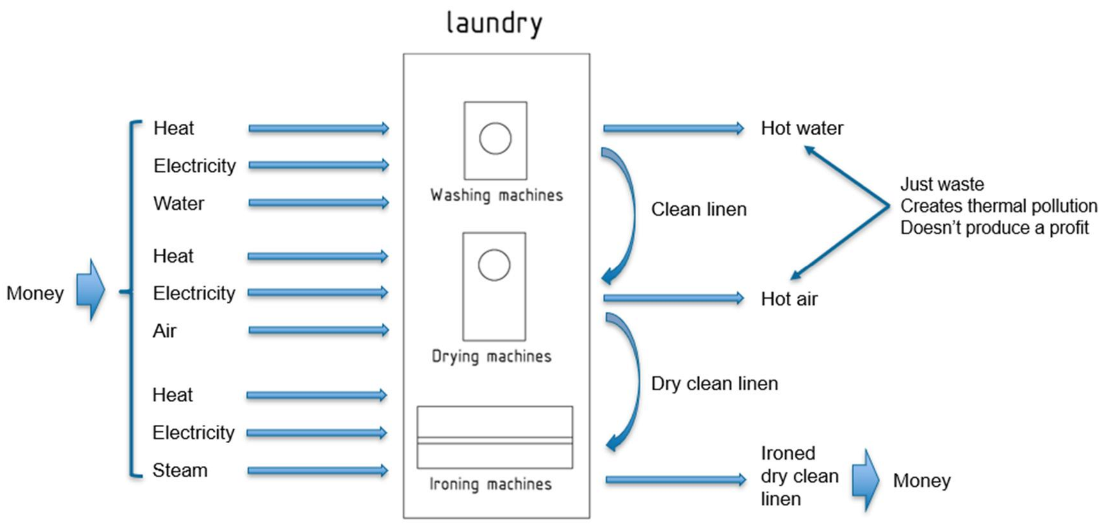

Figure 1. Scheme of the cycle of a laundry enterprise

Heat, electricity and water are used to carry out the washing cycle, in the process of washing clothes, hot water is released into the sewer and clean but wet clothes. Hot water is discharged into the sewerage system and does not benefit in any way. /4/

Drying cycle. The cycle requires heat, as well as electricity and air. As a result of this cycle, hot air is emitted without utilization and use of the heat that this air has. During this cycle, the laundry loses excess moisture. /3,4/

The final cycle is ironing. It is carried out using machine tools with copper drums into which hot steam is supplied. These drums smooth out the laundry passing between them. This cycle requires heated steam as well as electricity. /3,4/

2.2. Equipment used in subject laundry

Table 1. List of equipment used in the project

Name	Part of the equipment	Provider	Purpose
Automatic monorail system		WSP Systems BV Netherlands/Germany	Designed for sorting, weighing, storing, transporting and automatically unloading linen into a production washing line and finishing textiles
Inline washing line	Clock washing machine. LT 50-16	Lavatec Laundry Technology GmbH Germany	It is intended for washing, disinfection of direct and shaped linen. Moisture removal
	Press LP 572		
Ironing lines	Ironing roller D803G	Laco Machinery Belgium	Designed for ironing, stacking and sorting straight linen
	Feeding machines Vac Feed-29	H J Weir Equipment Great Britain	
	folding machine		

	Foldmaker 55		
Processing of Shaped Products	tunnel machine Variojet FTS-206/G	FINTEC Germany	Finishing of shaped textiles
Sterilizatio n	Sterilizer Colussi SA120	Colussi Italy	Sterilization of surgical textiles
Finishing of terry products	folding machine Flex Fold AT230	FOLTEX Netherlands	Folding and sorting terry products

When compiling this table, data from the websites of equipment suppliers was used.

3. DESCRIPTION OF OPTIONS TO INCREASE THE ENERGY EFFICIENCY OF THE ENTERPRISE

3.1. Analysis of energy efficiency optimization opportunities

There are several options for improving the energy efficiency of the laundry cycle. The key problem in this cycle is the very large thermal energy emissions from various equipment. /4/

The main places of heat release can be the following cycles of the laundry enterprise: washing process, laundry drying process, ironing process. Below is an analysis of these processes.

3.2. Washing process

During the washing process in washing machines, several basic cycles occur. Each of these cycles is discussed below to understand the temperature regime of washing, as well as to understand the water consumption in this cycle.

First of all, the laundry is sorted for various types of contamination, since, depending on the type of contamination, a different mode of the washing machine is provided, for example, for laundry with blood (a fairly common situation when washing linen coming from operating theaters and inpatient hospitals) laundry requires an initial rinse with cold water and hydrogen peroxide. After sorting, the laundry is loaded into the washing machine, in which the first washing cycle is performed. The first cycle in most cases is a rinse with cold water, water is supplied at a temperature of about 20-22 ° C, naturally, as a result of this cycle, not enough heat is released. After 2-3 rinse cycles, in most cases, there is a transition to the next washing mode, this cycle is the main one, since it occurs at high water temperatures: from 80 to 110 °C (The water temperature above 100°C without transition to another state of aggregation is possible due to the fact that the chamber of the washing machine maintains a pressure above atmospheric pressure). The cycle occurs in the time range of 20-50 minutes, respectively, in the process, a sufficiently large volume of water with an average temperature of 60-80 ° C is discharged into the sewerage network of the enterprise, which is simply discharged to the treatment plant without any heat removal. Naturally, this is an excellent opportunity to improve the energy efficiency of the system, since we can install a water-to-water heat pump circuit into waste water and remove heat, transferring it to water preheating in the same cycle, usually water comes from a well or from centralized water supply, depending on the location of the laundry enterprise, therefore, water can be of different temperatures in the range from 10 to 23 ° C, of course, heating it requires a significant amount of energy, in our case, due to the heat pump, we can preheat this water and spend many times less energy. Also, the water entering the sewer system after the removal of thermal energy causes much less harm to the environment (because hot water discharges contribute to environmental degradation). /3,5,6/

The final cycle in washing is rinsing clean linen in order to remove residual detergents and reduce the temperature of the linen after the previous cycle. For this, clean water with a temperature of 18-22 ° C is used. Rinsing usually takes place in 2 cycles, the first cycle is aimed at removing residual detergents and is quite contaminated with them, as a result of which this water cannot be reused, but the second cycle is mainly aimed at reducing the temperature of the laundry in the machine drum and consequently, after this cycle, it is suitable for reuse in a washing cycle at high temperature. Accordingly, if a recycling system is provided in the water supply and drainage system of the washing machine, water consumption can be reduced. /3,5,6/

3.3. Laundry drying process

After washing and spinning, the linen enters the dryers, since for the most efficient ironing process using industrial flow machines, the required moisture content of the linen varies from 20 to 40%, the drying process takes place in special dryers, in a machine with a rotating drum - no dry, hot (around 60 ° C) air with which the laundry is dried to the desired humidity. Drying usually takes place within 15-30 minutes and is accompanied by a continuous supply of hot air, which is subsequently simply drawn out and discharged into the surrounding atmosphere. This air has a temperature close to 75°C and can be released in several different cycles: /3,5,6/

A combined system using an air-to-air heat exchanger and a heat pump can also be used (this is possible due to the fact that the operating temperature of the heat pump, under conditions of high efficiency, can be significantly lower than the corresponding temperature for the heat exchanger). /3,7,8/

The use of an air-to-air heat pump that removes heat from the heated air stream after a drying cycle and preheats the air for the same cycle. The advantage of this option is that the heat pump not only raises the temperature of the flow subsequently supplied to the dryer, but also cools the air from which energy is extracted. /7/ One of the rather serious problems of drying and ironing workshops of laundries is that in these workshops, due to heat leakage from production cycles, a very high temperature regime is created, which naturally negatively affects the internal microclimate of these premises. With the help of a heat pump, which removes heat from the air flows from the dryers and from the internal air of the room (maybe in the region of 27-30 ° C) and cools the air to an acceptable temperature, which is subsequently supplied to the ventilation system of the drying shops. /3,4/ This can not only reduce the cost of heating the air supplied to the dryer, but also significantly reduce the cost of ventilation and air conditioning indoors. /3/

3.4. Ironing process

The final stage of the production cycle of the laundry enterprise is ironing. In industrial laundries, this is done with large ironing machines that have a large roller heated by hot steam or water. The bulk of the laundry washed in large industrial laundries is flat-type laundry. The linen is automatically rolled through the shaft heated to high temperatures, since the most effective is the ironing of linen with a humidity of 20 to 50% (dry linen is much more difficult to smooth out with industrial ironing machines), when the linen passes through the shaft (the shaft can be from 1 to 3x pieces) evaporation of moisture occurs, with which a large amount of heat is discharged into the internal air of the ironing shop, which can also be removed by heat exchangers and heat pumps, as well as when drying clothes. It can also significantly reduce production energy costs. /3,6/

4. CALCULATION OF THE PRODUCTION CHAIN AND THE COST OF A UNIT OF PRODUCTION TAKING INTO ACCOUNT THE INTRODUCTION OF THE ENERGY EFFICIENCY SYSTEM

One of the simplest and most effective ways to increase the energy efficiency of a wash cycle is to make the most of wastewater heat after washing at high water temperatures. The second promising approach in the use of waste heat is the use of heat after drying clothes. /3,4/

In this chapter analysis of these two options is made. Also, necessary calculations are made. The main idea of these calculations will be a comparison of two energy efficiency systems.

The first option involves installing a heat exchanger after the wash cycle, in order to use the hot water generated during the hot rinse in the washing machine to preheat the water from the well to the cold rinse temperature in the washing machine. /3,4/

The second option considers the installation of a heat exchanger after the dryer. This heat exchanger receives hot air, which is formed as a result of the operation of the dryer and transfers its thermal energy to the air that enters the dryer. /3,4/

Schematic diagrams for these two options are shown in figure 2.

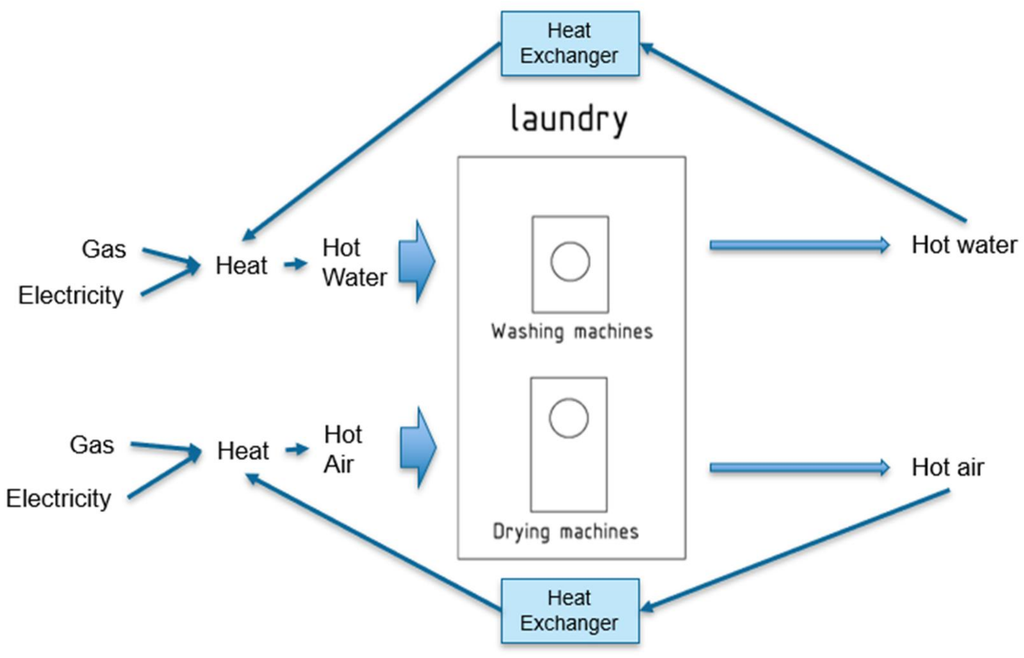

Figure 2. Schematic diagrams of opportunities to improve energy efficiency

The comparison criterion will be the amount of energy that we can save when using the considered energy efficiency systems. But since the number of washing machines and dryers in the laundry under consideration is different, the objective indicator for comparison will be the amount of energy that can be saved when washing or drying 1 kilogram of laundry. This indicator will be objective, since the amount of laundry that passes through the washing machines and dryers is the same. /3/

In the next chapter, Table 2 will present the initial data that will be used in the calculations.

4.1. Analysis of initial data for a washing machine

Some initial data obtained as a result of the analysis of the technical and operational indicators of the LT 50-16 tunnel type washing machine (manufacturer LAVATEC). Summarized in table 2. /3/

Table 2. Initial data for calculating the tunnel washing machine

Tunnel Washer LT 50-16 (LAVATEC)		
Water	9750	L / h
Compressed air	120	L / h
Steam	600	kg/h
Electrics consumption apr	21.1	kW/h
Electrics MAX	24	kW/h
Weights	17000	kg
Floor load	2.2	kg/cm²
Amount of linen for 1 hour	1200	kg/h
Plane coordinates	C12 - C15	

Water parameter describes the amount of water required to complete all cycles of the tunnel washing machine. A feature of this type of washing machines is that they are divided into a number of compartments, in each of which a separate washing cycle takes place in parallel (Illustration of these compartments can be seen in figure 3). The laundry enters the first compartment, goes through the washing cycle provided in the first compartment, then enters the next compartment, while a new portion of laundry enters the first compartment. /5/ That is, the water consumption for each hour of operation of the machine is uniform for each of the compartments (with the exception of the first and last cycles after starting the washing machine). /3/

The intention of the calculation is to illustrate the fundamental concept of enhancing energy efficiency. Presented below is a table (Table 4) outlining the primary washing cycles, along with their usual temperatures and water flow rates. The initial assumptions consider the washing machine's design to include compartments matching the number of washing cycles. Using this as a basis, subsequent calculations were performed to optimize energy efficiency.

Compressed air parameter is not considered in the calculation, since, during the operation of the washing machine, compressed air is mainly used for the mechanical movement of some parts of the washing machine according to the principles of pneumatics. Optimizing the consumption of this indicator is not the purpose of this calculation. /3/

Steam. The main heat carrier in the laundry under consideration is superheated steam, which is heated in the boiler room, and then with its help, water is heated for the washing cycle with a high-water temperature. The use of steam is necessary to link the amount of energy required to heat water in different cycles and the cost of heating it. /3/

Washing machine motor energy consumption is the electrical energy that is used to start the washing machine motor, which produces the mechanical movement of the drums inside the compartments and drives. In the calculation, this value is considered only as part of the energy cost for the entire cycle. But it cannot be optimized.

Maximum motor power consumption is the maximum value of the previous parameter, so this value will also not be considered, in the calculation.

4.2. Analysis of initial data for the dryer

Table 3 below provides the initial data for the dryer calculation.

Table 3. Initial data for the calculation of the dryer

Drying machine Vyazma VS-20		
Air flow	540	m^3/h
Energy per drive motor	0.75	kW/h
Energy per fan motor	0.37	kW/h
Energy for heating elements	24	kW/h
Drying temperature	90	°C
Amount of linen for 1 hour	40	kg/h
Plane coordinates	A-B, 12-16	

Parameter air flow shows how much air is required to run the dryer for 1 hour. Air enters the machine at room temperature, i.e. approximately 19 °C and then heated to operating temperature. /3/

Energy per drive motor parameter shows how much energy is spent in one hour of work to rotate the motor that drives the dryer drum. /3/

The energy per fan motor is the amount of energy required to operate the air pump, which draws air into the interior of the tumble dryer. This parameter will not be used in further calculations, since it is impossible to reduce the energy consumption for pumping air using a heat exchanger, which will increase the energy efficiency of the dryer. /3,4/

The energy for heating elements is the amount of energy that goes into heating the air from room temperature to the temperature required in the drying cycle. /3/ This parameter will change when a heat exchanger is added to the system. This will reduce the amount of energy provided that the air entering the drum is preheated with the same energy as the air leaving the dryer (its temperature is around 75°C). /4/

Drying temperature is the temperature at which the process of drying clothes in the tumble dryer takes place. /3/ Naturally, inside the machine there is a loss of temperature of this air, due to losses for heating the laundry inside the drums and losses for heating the elements of the machine itself, as a result of which we have air with a temperature of about 75 ° C at the outlet of the dryer. This energy will be used to pre-heat the air entering the dryer. /4/

4.3. Energy calculation for a washing machine

The structure of the energy efficiency system is primarily determined by the working fluid from which heat will be removed, in the first case it is water. Below, in figure 3, there is a schematic diagram of an energy efficiency system with a heat exchanger after washing cycles with separate wastewater disposal after each wash cycle.

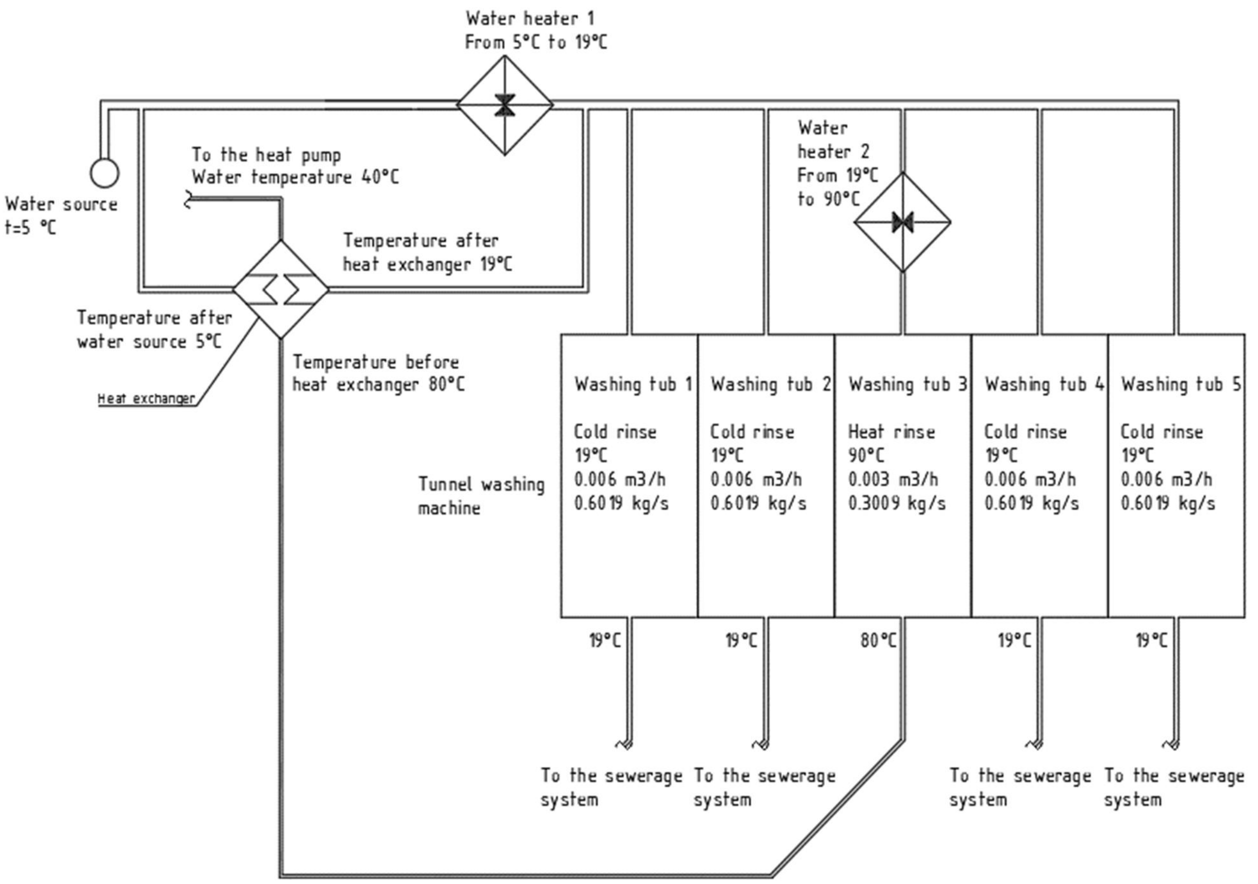

Figure 3. Schematic diagram of an energy efficiency system with a heat exchanger after washing cycles with separate wastewater disposal after each wash cycle

The typical structure of wash cycles, which can be applied to almost any wash cycle, with the exception of specialized laundry (for example, woolen products, overalls, synthetics, etc.). The first cycle is always a rinse with running cold water. Detergents are not usually used in this cycle, the temperature of the water used in the cycle is around 19 °C. The second cycle is usually carried out with the same flow of water at the same temperature, but with the use of detergents. The third cycle is performed at high water temperature. High-temperature water is supplied to the drum of the washing machine (or cold water is supplied, which inside the drum is heated to a temperature of 90-100 °C), then the laundry is rinsed at this temperature with detergents. Next, hot water is usually discharged into the sewer system. The fourth and fifth cycles are rinsing clothes with water at a temperature of 19 ° C. All 4 rinse cycles with cold water take place with an equal supply of water and water with a temperature of about 19 °C. /3,4/

Below is a summary table 4 with a breakdown by washing cycles and an indication of the temperatures and water consumption in each cycle for 1 hour of the washing machine.

Table 4. Data on temperature and water consumption in washing cycles

Cycles per hour (since the machine is a tunnel machine, all cycles are parallel)							
№	Cycle name	t_c	Unit	Water consumption	Unit	Water consumption per hour	Unit
1	Rinse 1	19	°C	2166.7	L	2.2	m^3
2	Rinse 2	19	°C	2166.7	L	2.2	m^3
3	Heat rinse	90	°C	1083.3	L	1.1	m^3
4	Rinse 3	19	°C	2166.7	L	2.2	m^3
5	Rinse 4	19	°C	2166.7	L	2.2	m^3

Below are some of the conditions present in the calculations:
The temperature of the water coming from the water source is 5 °C.

Based on these data, the energy costs for heating the water used in each cycle are calculated below.

$$Q_{h.w.} = c_p * m * (t_{out} - t_{in}) \tag{4.1}$$

$Q_{h.w.} - energy\ for\ heating\ water\ for\ a\ given\ temperature\ difference, kJ$

$c_p - heat\ capacity\ of\ water$ 4,2 $kJ/\mathrm{k}g *$ °C

$m - mass\ of\ heated\ water, kg$

$t_{out} - water\ temperature\ after\ heating,$ °C

$t_{in} - water\ temperature\ before\ heating$, °C

$$\Phi_{h.w.} = c_p * \rho * q_v * (t_{out} - t_{in}) \tag{4.2}$$

$\Phi_{h.w.} - power\ for\ heating\ water\ for\ a\ given\ temperature\ difference, kW$

$c_p - heat\ capacity\ of\ water$ 4,2 $kJ/$kg $*$ °C

$\rho - density\ of\ water, kg/m^3$

$q_v - volume\ flow\ of\ water, m^3/h$

$t_{out} - water\ temperature\ after\ heating$, °C

$t_{in} - water\ temperature\ before\ heating$, °C

The calculations are summarized in table 5.

Table 5. Data on outlet temperature, volume flow and energy consumption in wash cycles.

Cycles per hour (since the machine is a tunnel machine, all cycles are parallel)							
№	Cycle name	Temp at the exit from the cycle	Unit	Vol. water flow	Unit	Energy consumption	Unit
1	rinse 1	19	°C	0.0006	m3/h	35.4	kWh
2	rinse 2	19	°C	0.0006	m3/h	35.4	kWh
3	Heat rinse	80	°C	0.0003	m3/h	214.9	kWh
4	rinse 3	19	°C	0.0006	m3/h	35.4	kWh
5	rinse 4	19	°C	0.0006	m3/h	35.4	kWh
						356.4	kWh

This table shows how much heat energy needs to be spent on heating water for all washing cycles for 1 hour of washing machine operation. The temperature of the water discharged to the sewer is 80 °C, this temperature can be used to preheat the water coming from the well. To do this, it is necessary to calculate the heat exchanger.

The mass flow in the washing cycle is calculated according to formula 4.3.

$$q_m = q_v * \rho \tag{4.3}$$

$q_m - mass\ flow\ of\ water, kg/h$

$\rho - density\ of\ water, take$ 1000 kg/m^3

$q_v - volume\ flow\ of\ water, m^3/h$

Mass and volume costs in each wash cycle are presented in the form of table 6.

Table 6. Data on mass and volume flow rates in wash cycles

№	Cycle name	q_v	Unit	q_m	Unit
1	Rinse 1	0.0006	m^3/s	0.6019	kg/s
2	Rinse 2	0.0006	m^3/s	0.6019	kg/s
3	Heat rinse	0.0003	m^3/s	0.3009	kg/s
4	Rinse 3	0.0006	m^3/s	0.6019	kg/s
5	Rinse 4	0.0006	m^3/s	0.6019	kg/s

Further, the amount of energy obtained is calculated if the hot water at the outlet of the heat exchanger has a temperature of 40 ° C. This temperature value is set for the subsequent use of the heat pump (it is provided in this work, but not calculated). For this formula 4.1 is used. Calculations are simplified using formula 4.3. /7,9,10/

$$Q_{h.w.} = c_p * m * (t_{out} - t_{in}) \tag{4.4}$$

Numerical values in formula 4.4 are substituted below

$$\Phi_{h.w.} = 4.2\ (kJ/\text{kg} * °\text{C}) * 0.3009\ kg * (80\ °\text{C} - 40\ °\text{C}) = 50.55\ kW \tag{4.5}$$

Part of the heat in the process of heat exchange will be lost due to transport losses and heat losses of the heat exchanger itself. The system efficiency is assumed to be 85%. Formula 4.6 expresses the amount of energy that heated water can receive in the process of heat transfer. /9,10/

$$Q_{c.w.} = \eta * Q_{h.w.} \tag{4.6}$$

$Q_{c.w.} - energy\ received\ by\ cold\ water\ in\ the\ process\ of\ heat\ exchange, kW$

$Q_{h.w.} - energy\ given\ off\ by\ hot\ water\ in\ the\ process\ of\ heat\ exchange, kW$

$\eta - system\ efficiency$, %

Numerical values in formula 4.6 are substituted below

$$Q_{c.w.} = 0.85 * 50.55\ kW = 42.97\ kW \quad (4.7)$$

"Kilowatt" is a multiple of "watt", the system unit of power. “kilowatt-hour” is an off-system unit for accounting for consumed or produced energy. Since the amount of energy received by cold water in the process of heat exchange is the amount of energy saved that will not be required to heat water for the next cycles, we introduce a new value that will be numerically equal to the amount of energy received by cold water in the process of heat exchange, but will show the amount of energy saved in the process heat exchange and will be calculated in kWh.

$$\Phi_{c.w.} = 42.97\ kWh \quad (4.8)$$

$Q_{c.w.} - the\ amount\ of\ energy\ saved\ in\ the\ process\ of\ heat\ exchange, kWh$

The washing machine has a capacity of 1200 kg of laundry per hour, from this data it is calculated the amount of energy required to heat water to wash 1 kg of laundry. /6,7,9/

$$\Phi_{w.kg} = \frac{\Phi_{w.tot}}{A} \quad (4.9)$$

$\Phi_{w.kg} - the\ amount\ of\ energy\ required\ to\ wash\ 1\ kilogram\ of\ laundry, kWh$
$\Phi_{w.tot} - energy\ to\ heat\ water\ to\ run\ a\ washing\ machine\ for\ an\ hour, kWh$
$A - amount\ of\ laundry\ washed\ in\ 1\ hour, kg$

Numerical values in formula 4.9 are substituted below

$$\Phi_{w.kg} = \frac{356.4\ kWh}{1200\ kg} = 0.297\ kWh/kg \quad (4.10)$$

The amount of energy saved is substracted when using a heat exchanger from the total amount of energy and the amount of energy needed to wash one kilogram of laundry with an implemented energy efficiency system is calculated using formula 4.11. /9,10/

$$\Phi_{we.kg} = \frac{\Phi_{w.tot} - \Phi_{c.w.}}{A} \tag{4.11}$$

$\Phi_{we.kg}$ – *the amount of energy needed to wash* 1 *kilogram of laundry with an implemented energy efficiency system*, *kWh*
$\Phi_{w.tot}$ – *energy to heat water to run a washing machine for an hour*, *kWh*
$\Phi_{c.w.}$ – *energy received by cold water in the process of heat exchange*, *kW*
A – *amount of laundry washed in* 1 *hour*, *kg*

Numerical values in formula 4.11 are substituted below

$$\Phi_{we.kg} = \frac{356.4\,kWh - 42.97\,kWh}{1200\,kg} = 0.261\,kWh/kg \tag{4.12}$$

Formula 4.13 is used to calculate the amount of energy that is saved from each kilogram of laundry washed after the introduction of an energy efficiency system. /9,10/

$$\Phi_{sw.kg} = \Phi_{w.kg} - \Phi_{we.kg} \tag{4.13}$$

$\Phi_{sw.kg}$ – *the amount of energy saved in the process of washing* 1 *kilogram of laundry using an energy efficiency system*, *kW*

Numerical values in formula 4.13 are substituted below

$$\Phi_{s.kg} = 0.297\,kWh/kg - 0.261\,kWh/kg = 0.036\,kWh/kg = 36\,Wh/kg \tag{4.14}$$

The capacity of the laundry for a year is 1900 tons of linen per year, below is the calculation of how much energy can be saved during the year by using an energy efficiency system. /9/

$$\Phi_{w.a} = \Phi_{s.kg} * A_a \tag{4.15}$$

$\Phi_{w.a} - amount\ of\ energy\ saved\ in\ 1\ year, kWh$
$A_a - number\ of\ kilograms\ of\ laundry\ washed\ per\ year, kWh$

Numerical values in formula 4.15 are substituted below

$$\Phi_{w.a} = 36\ Wh/kg * 1900000\ kg = 68400000\ W = 68.4\ MWh \tag{4.16}$$

For 1 year of operation of an energy efficiency system with a heat exchanger after a washing cycle, 68.4 MWh of energy can be saved.

4.4. Dryer energy calculation

First of all, a schematic diagram of a system for increasing the energy efficiency of the drying cycle using a heat exchanger was drawn up. It is presented below in figure 2.

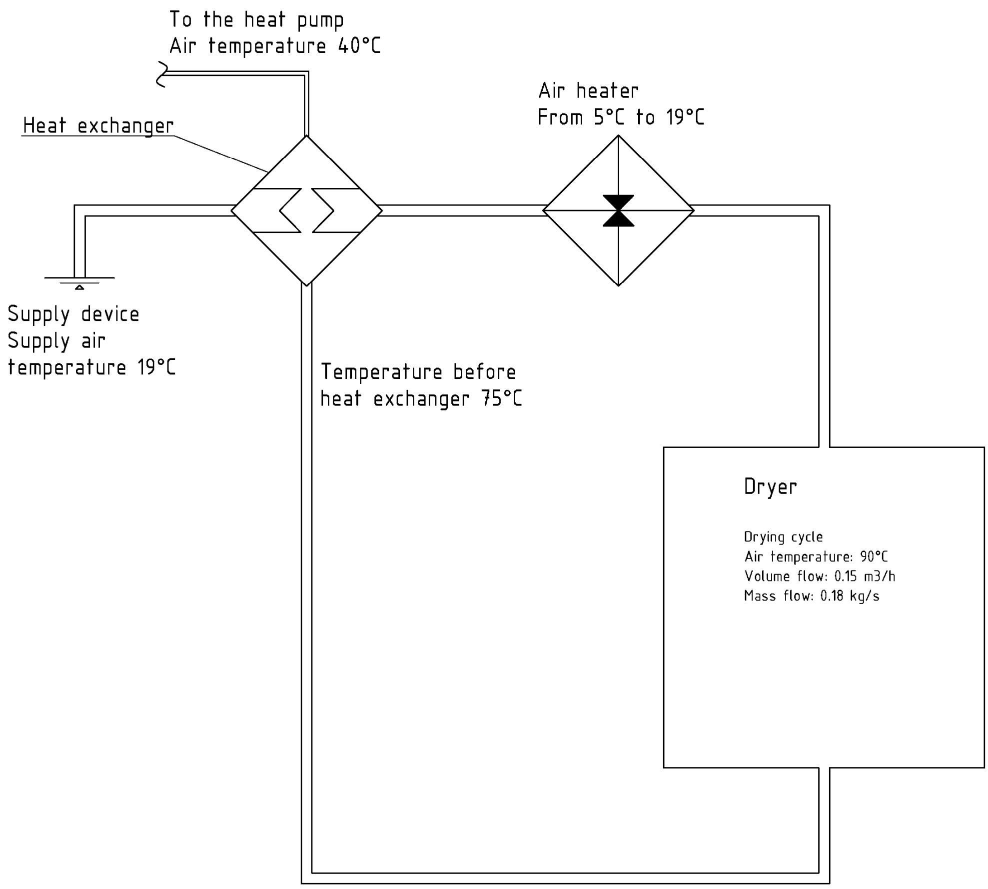

Figure 4. Schematic diagram of the system for increasing the energy efficiency of the drying cycle using a heat exchanger

During the drying process, we have a constant temperature, which is maintained in the dryer drum, so it is not necessary to break the process into separate cycles. /3,4/ Below is the drying cycle table.

Table 7. Tumble dryer temperature and airflow data

№	Cycle name	Inlet air temperature	Outlet air temperature	Air consumption per hour	points	Air consumption per second	points
1	Drying process	19 °C	90 °C	540.0	m^3/h	0.15	m^3/s

Equation 4.2 for drying laundry. Since in this case heat exchange occurs between the air flows, equation 4.2 will take the following form. /9,10/

$$\Phi_{h.w.} = c_p * \rho * q_v * (t_{out} - t_{in}) \quad (4.17)$$

$\Phi_{h.w.}$ $-$ *power for heating air for a given temperature difference*, kJ/s

c_p $-$ *heat capacity of air*, *take* 1 $kJ/(kg * °C)$

ρ $-$ *density of air*, *take* 1,2 kg/m^3

q_v $-$ *volume flow of air*, m^3/s

t_{out} $-$ *air temperature after heating*, °C

t_{in} $-$ *air temperature before heating*, °C

Substitute the numerical values in the formula 4.13

$$\Phi_{h.w.} = 1\ (kJ/(kg * °C)) * 1.2\ kg/m^3 * 0.15\ m^3/s * (90\ °C - 19\ °C) = 12.78\ kW \quad (4.14)$$

The mass air flow in the drying cycle is calculated according to formula 4.18.

$$q_m = q_v * \rho \quad (4.18)$$

q_m $-$ *mass flow of air*, kg/h

ρ $-$ *density of air*, *take* 1,2 kg/m^3

q_v $-$ *volume flow of air*, m^3/h

Numerical values in formula 4.18 are substituted below

$$q_m = 0.15\ m^3/h * 1.2\ kg/m^3 = 0.18\ kg/h \quad (4.19)$$

Next, you can calculate how much energy is obtained if the hot air at the outlet of the heat exchanger has a temperature of 40 °C heat pump could be considered to use the heat below this temperature level. Heat pump is not calculated in this work. However, an air-to-air heat exchanger cannot be used for a long time if water condensation occurs during the heat exchange due to a decrease in temperature. /3,4,12/ The maximum temperature at which condensation will not occur is calculated below.

The humidity of the laundry after spinning before entering the dryer is on average around 55%. The humidity of the laundry after the dryers for the best process of ironing the laundry should be about 30%. To operate for one hour, the dryer requires 540 m^3 of air, air with the parameters of static room air, its relative humidity is about 20%, and the moisture content is about 7 g/m^3. The capacity of the dryer is 40 kilograms of laundry per hour. Moisture before drying the linen is approximately 55% of the weight of dry linen, and at the end of the drying cycle, approximately 30%, therefore, in 1 hour, an amount of water equal to 25% of the mass of linen entering the dryer for 1 hour evaporates into the exhaust air. /3,4,12/ In formula 4.20, the moisture content of the air exhausted from the dryer is calculated.

$$x_h = \frac{(0.25 * A_a)}{m_{e.a.}} + x_{n.a.} \tag{4.20}$$

$x_h - moisture\ content\ of\ the\ air\ exhausted\ from\ the\ dryer, g/kg$
$A_a - amount\ of\ laundry\ to\ be\ dried\ in\ 1\ hour, kg$
$x_{n.a.} - moisture\ content\ of\ the\ air\ entering\ the\ dryer, g/kg$
$m_{e.a.} - mass\ of\ air\ entering\ the\ dryer, kg$

Numerical values in formula 4.20 are substituted below

$$x_h = \frac{(0.25 * 40\ kg) * 1000}{648\ kg} + 7\ g/kg = 22.4\ g/kg \tag{4.21}$$

With a moisture content value of 22.4, the moisture condensation temperature is 26.8 °C. The outlet temperature of the heat exchanger must be set to at least the condensing temperature. Therefore, if the air at the outlet of the heat exchanger has a temperature of 40 ° C, condensation will not occur. /4,9,12/

For this formula 4.18 is applied. Calculations are simplified using formula 4.19. /9/

$$\Phi_{h.a.} = c_p * q_m * (t_{out} - t_{in}) \tag{4.22}$$

Numerical values in formula 4.22 are substituted below

$$\Phi_{h.a.} = 1\ (kJ/\text{kg} * ℃) * 0.18\ kg/h * (75\ ℃ - 40\ ℃) = 6.3\ kW \tag{4.23}$$

As in the calculation of the heat exchanger after washing cycles, part of the heat in the heat exchange process will be lost due to transportation losses and heating losses of the heat exchanger itself. Let us take the efficiency of the system equal to 85%. Let us express the amount of energy that the heated air can receive in the process of heat transfer. /8/

$$\Phi_{c.a.} = \eta * \Phi_{h.a.} \tag{4.24}$$

$\Phi_{c.a.} - energy\ received\ by\ cold\ air\ in\ the\ process\ of\ heat\ exchange, kWh$
$\Phi_{h.a.} - energy\ given\ off\ by\ hot\ air\ in\ the\ process\ of\ heat\ exchange, kWh$
$\eta - heat\ exchanger\ efficiency, \%$

Numerical values in formula 4.24 are substituted below

$$\Phi_{c.a.} = 0.85 * 6.3\ kWh = 5.36\ kWh \tag{4.25}$$

The dryer has a capacity of 40 kg of laundry per hour, from this data it is calculated the amount of energy required to heat the air to dry 1 kg of laundry. /3/

$$\Phi_{a.kg} = \frac{\Phi_{a.tot}}{A} \tag{4.26}$$

$\Phi_{a.kg} - the\ amount\ of\ energy\ required\ to\ wash\ 1\ kilogram$
$of\ laundry, kWh/kg$
$\Phi_{a.tot} - energy\ to\ heat\ water\ to\ run\ a\ washing\ machine\ for\ an\ hour, kWh$
$A - amount\ of\ laundry\ washed\ in\ 1\ hour, kg$

Numerical values in formula 4.26 are substituted below

$$\Phi_{a.kg} = \frac{12.78\,kWh}{40\,kg} = 0.320\,kWh/kg \qquad (4.27)$$

The amount of energy saved when using a heat exchanger from the total amount of energy is subtracted and the amount of energy needed to dry one kilogram of laundry with an implemented energy efficiency system s calculated using formula 4.23. /8/

$$\Phi_{ae.kg} = \frac{\Phi_{a.tot} - \Phi_{c.a.}}{A_a} \qquad (4.28)$$

$\Phi_{ae.kg} - the\ amount\ of\ energy\ needed\ to\ dry\ 1\ kilogram\ of\ laundry\ with\ an\ implemented\ energy\ efficiency\ system, kWh/kg$
$\Phi_{a.tot} - energy\ to\ heat\ air\ to\ run\ a\ drying\ machine\ for\ an\ hour, kWh$
$A_a - amount\ of\ laundry\ to\ be\ dried\ in\ 1\ hour, kg$

Numerical values in formula 4.28 are substituted below

$$\Phi_{ae.kg} = \frac{12.78\,kWh - 5{,}36\,kWh}{40\,kg} = 0.186\,kWh/kg \qquad (4.29)$$

Using formula 4.30, the amount of energy that is saved from each kilogram of laundry after the introduction of an energy efficiency system is calculated. /3,8/

$$\Phi_{sa.kg} = \Phi_{a.kg} - \Phi_{ae.kg} \qquad (4.30)$$

$\Phi_{sa.kg} - the\ amount\ of\ energy\ saved\ in\ the\ process\ of\ drying\ 1\ kilogram\ of\ laundry\ using\ an\ energy\ efficiency\ system, kWh/kg$

Numerical values in formula 4.30 are substituted below

$$\Phi_{s.kg} = 0.320\,kW/kg - 0.186\,kW/kg = 0{,}134\,kW/kg = 134\,W/kg \qquad (4.31)$$

The capacity of the laundry for a year is about 1900 tons of linen per year, it is calculated below how much energy can be saved in a year with this energy-saving system. /3,8/

$$\Phi_{a.a} = \Phi_{s.kg} * A_a \tag{4.32}$$

$\Phi_{a.a} - amount\ of\ energy\ saved\ in\ 1\ year, kWh$
$A_a - number\ of\ kilograms\ of\ laundry\ washed\ per\ year, kg$

Numerical values in formula 4.32 are substituted below

$$\Phi_{w.a} = 134\ Wh/kg * 1900000\ kg = 254600000\ Wh \tag{4.33}$$

For 1 year of operation of an energy efficiency system with a heat exchanger after a drying cycle, 254.6 MWh of energy can be saved.

4.5. Comparison of energy efficiency systems

A comparison was made between two different energy efficiency systems. The best of them was the one in which the heat exchanger is used after the dryer. Naturally, the best option is to use two systems at once, but heat exchangers designed for high flows and high temperatures are quite expensive. /3,4/

At this point, an analysis was made of the performance of the two systems and one of the biggest differences in the efficiency of the two heat exchange systems is the different mass flows. In a system with a heat exchanger after washing the laundry, we have 6 cycles, but heat is used from only one cycle, which is the hottest. In a system including a heat exchanger, the situation is completely different after the dryer. Since there is only 1 cycle in the dryers in general, all the air that is emitted during the operation of the machine has a high temperature. /3,4/

In the following calculations, some changes have been made to the heat exchanger system provided after the wash cycles, which can increase the amount of energy saved used to wash 1 kg of laundry. /3,4/

4.6. Energy calculation for a washing machine using wastewater mixing

First of all, a schematic diagram of an energy efficiency system with a heat exchanger after washing cycles with a common wastewater outlet was drawn up. It is presented below in figure 5.

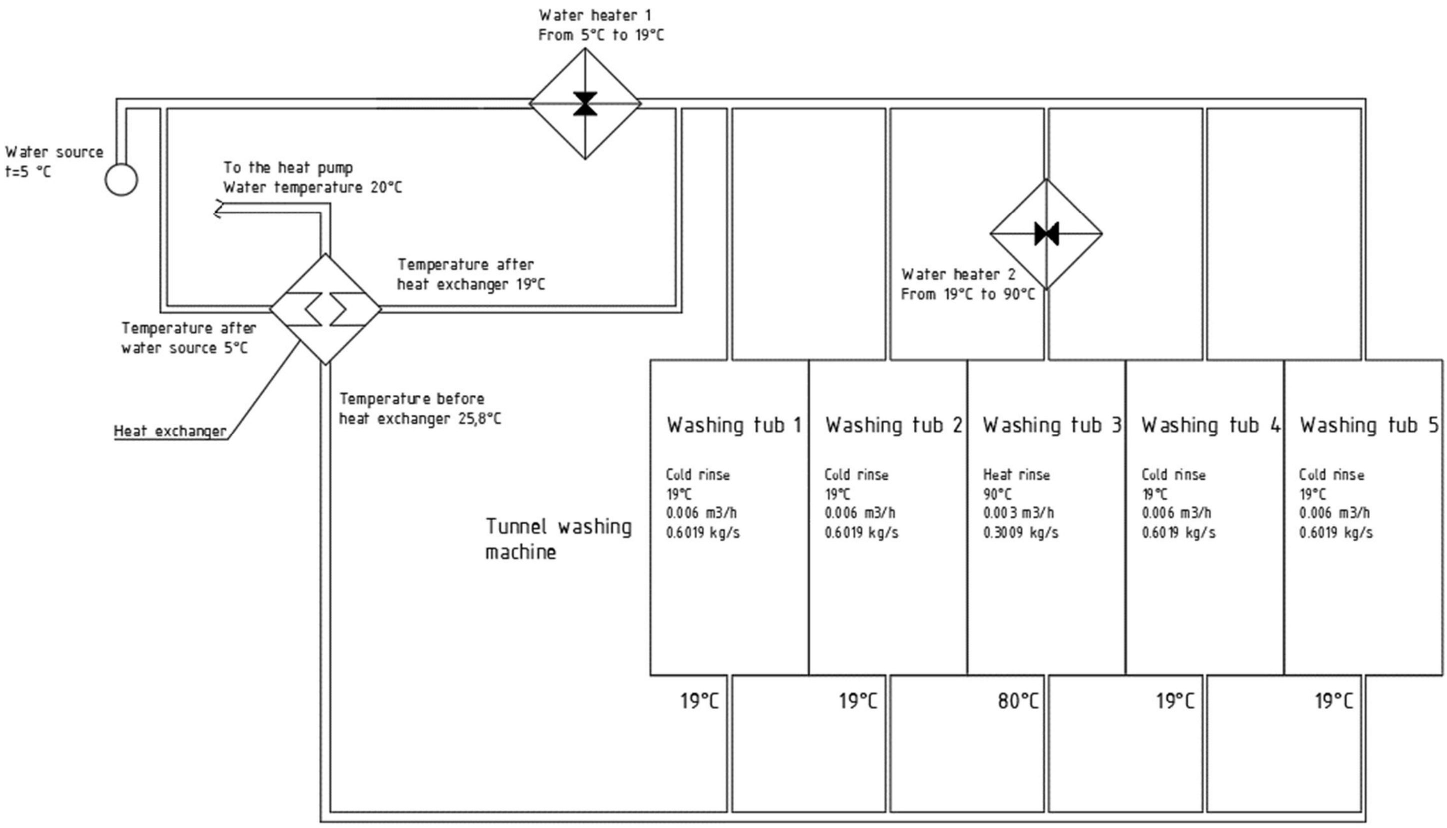

Figure 5. Schematic diagram of an energy efficiency system with a heat exchanger after washing cycles with a common wastewater outlet

The main difference from the previous system for improving energy efficiency by installing a heat exchanger after washing cycles is the connection of wastewater after it is discharged into the sewer. In this case, this wastewater is first passed through a heat exchanger to preheat the water entering the washing machine. The temperature of the mixed wastewater after hot and cold cycles is calculated below.

When mixing water, the field of two cold cycles with a water temperature of 19°C, their mass flows add up, and the temperature remains unchanged. /3,4/

After that, the water from the two cold cycles is mixed with water, which is discharged into the sewerage system after the hot cycle, it has a temperature of 80°C. Below is formula 4.35, which calculates the temperature after mixing these two streams. /3,9,10/

$$\Phi_{c.w.m.} = \Phi_{h.w.m.} \tag{4.35}$$

$Q_{c.w.m.} - the\ amount\ of\ energy\ received\ by\ cold\ water\ in\ the\ mixing\ process, kW$

$Q_{c.w.m.} - the\ amount\ of\ energy\ given\ off\ by\ hot\ water\ during\ the\ mixing\ process, kW$

In formula 4.36, formula 4.35 is expressed in terms of other quantities and transformed into a system of linear equations with two unknowns.

$$\begin{cases} Q_{c.w.m.} = c_p * q_{m.c.} * (t_m - t_c) \\ Q_{h.w.m.} = c_p * q_{m.h.} * (t_h - t_m) \\ Q_{c.w.m.} = Q_{h.w.m.} \end{cases} \tag{4.36}$$

$q_{m.c.} - total\ mass\ flow\ from\ 4\ cold\ cycles, kg/s$

$q_{m.h.} - mass\ flow\ from\ hot\ cycle, kg/s$

$c_p - heat\ capacity\ of\ water\ 4{,}2\ kJ/\mathrm{k}g * °\mathrm{C}$

$t_m - mixed\ water\ temperature\ after\ 4\ cold\ and\ hot\ cycles, °\mathrm{C}$

$t_h - water\ temperature\ after\ hot\ cycle, °\mathrm{C}$

$t_c - water\ temperature\ after\ cold\ cycle, °\mathrm{C}$

Numerical values in formula 4.36 are substituted below

$$\begin{cases} Q_{c.w.m.} = 4.2\ (kJ/\mathrm{k}g * °\mathrm{C}) * (4 * 0.6019\ kg) * (t_m - 19\ °\mathrm{C}) \\ Q_{h.w.m.} = 4.2\ (kJ/\mathrm{k}g * °\mathrm{C}) * 0.3009\ kg * (80\ °\mathrm{C} - t_m) \\ Q_{c.w.m.} = Q_{h.w.m.} \end{cases} \tag{4.37}$$

The solution of this system of equations was carried out using programs for automatic calculation of linear equations. /11/

Equation solution:

$$Q_{c.w.m.} = Q_{h.w.m.} = 68.53\ kW$$
$$t_m = 25.78\ ℃$$

Below is a calculation similar to the above calculation of the heat exchanger after washing cycles with separate wastewater disposal after each cycle. /3,9,10/

$$Q_{h.w.2} = c_p * q_h * (t_m - t_{in.2}) \quad (4.38)$$

$Q_{h.w.2} - thermal\ energy\ given\ off\ by\ hot\ water\ when\ using\ the$
$combined\ sewerage,\ kWh$
$c_p - heat\ capacity\ of\ water$ 4,2 $kJ/\text{kg} *$ ℃
$q_h - mass\ flow\ of\ hot\ water,\ kg/s$
$t_m - mixed\ water\ temperature\ after$ 4 $cold\ and\ hot\ cycles,$ ℃
$t_{in.2} - water\ temperature\ after\ the\ heat\ exchanger\ in\ case\ of\ using\ a$
$mixed\ drainage\ system,$ ℃

Numerical values in formula 4.38 are substituted below

$$Q_{h.w.2} = 4.2\ \left(\frac{kJ}{\text{kg} * ℃}\right) * (0.3009\ kg/s + 4 * 0.6019\ kg/s) * (25.78\ °C - 20\ °C) =$$
$$= 65.75\ kWh \quad (4.39)$$

Part of the heat in the process of heat exchange will be lost due to transport losses and heat losses of the heat exchanger itself. The system efficiency is assumed to be 85%. Formula 4.40 expresses the amount of energy that heated water can receive in the process of heat transfer. /3,9,10/

$$Q_{c.w.2} = \eta * Q_{h.w.2} \quad (4.40)$$

$Q_{c.w.2} - thermal\ energy\ received\ by\ cold\ water\ when\ using$
$combined\ sewerage,\ kW,\ kW$
$\eta - system\ efficiency,$ %

Numerical values in formula 4.40 are substituted below

$$Q_{c.w.2} = 0.85 * 65.75\,kW = 55.89\,kW \tag{4.41}$$

The washing machine has a capacity of 1200 kg of laundry per hour, from this data the amount of energy required to heat water to wash 1 kg of laundry is calculated. /3,9,10/

$$\Phi_{w.kg} = \frac{\Phi_{w.tot}}{A} \tag{4.42}$$

$\Phi_{w.kg} - the\ amount\ of\ energy\ required\ to\ wash\ 1\ kilogram\ of\ laundry, kWh$
$\Phi_{w.tot} - energy\ to\ heat\ water\ to\ run\ a\ washing\ machine\ for\ an\ hour, kWh$
$A - amount\ of\ laundry\ washed\ in\ 1\ hour, kg$

Numerical values in formula 4.42 are substituted below

$$\Phi_{w.kg} = \frac{356.4\ \text{kWh}}{1200\ kg} = 0.297\ kWh/kg \tag{4.43}$$

Below the amount of energy saved by using the heat exchanger from the total amount of energy the amount of energy needed to wash one kilogram of laundry with an implemented energy efficiency system using formula 4.45. /3,9,10/

$$\Phi_{we.kg.2} = \frac{\Phi_{w.tot} - \Phi_{c.w.2}}{A} \tag{4.44}$$

$\Phi_{we.kg.2} - the\ amount\ of\ energy\ needed\ to\ wash\ 1\ kg\ of\ laundry\ with$
$implemented\ energy\ efficiency\ system\ with\ mixed\ wastewater\ disposal, kWh$
$\Phi_{w.tot} - energy\ to\ heat\ water\ to\ run\ a\ washing\ machine\ for\ an\ hour, kWh$
$A - amount\ of\ laundry\ washed\ in\ 1\ hour, kg$

Numerical values in formula 4.44 are substituted below

$$\Phi_{we.kg.2} = \frac{356.4\ kWh - 55.89\ kWh}{1200\ kg} = 0.25\ kWh/kg \quad (4.45)$$

Formula 4.46 is used to calculate the amount of energy that is saved from each kilogram of laundry washed after the introduction of an energy efficiency system. /4/

$$\Phi_{sw.kg.2} = \Phi_{w.kg} - \Phi_{we.kg.2} \quad (4.46)$$

$\Phi_{sw.kg.2} - the\ amount\ of\ energy\ saved\ in\ the\ process\ of\ washing\ 1\ kilogram\ laundry\ using\ an\ energy\ efficiency\ system\ with\ mixed\ wastewater\ disposal, kW$

Numerical values in formula 4.4 are substituted below

$$\Phi_{s.kg.2} = 0.297\ kWh/kg - 0.25\ kWh/kg = 0.047\ kWh/kg = 47\ Wh/kg \quad (4.47)$$

The capacity of the laundry for a year is about 1900 tons of linen per year, below is the calculation of how much energy can be saved during the year by using an energy efficiency system. /3/

$$\Phi_{w.a.2} = \Phi_{s.kg.2} * A_a \quad (4.48)$$

$\Phi_{w.a.2} - amount\ of\ energy\ saved\ in\ 1\ year\ using\ a\ mixed\ wastewater\ system, Wh/kg$

$A_a - number\ of\ kilograms\ of\ laundry\ washed\ per\ year, kW$

Numerical values in formula 4.48 are substituted below

$$\Phi_{w.a} = 47\ Wh/kg * 1900000\ kg = 89300000\ Wh = 89.3\ MWh \quad (4.49)$$

For 1 year of operation of the energy efficiency system with a heat exchanger after a wash cycle with a mixed wastewater system, 89.3 MWh of energy can be saved. /6,7/

4.7. Conclusion

When comparing the three energy efficiency systems, it is safe to say that the most profitable is the energy efficiency system that uses a heat exchanger after the drying cycle.

When analyzing two systems with post-wash cycle heat exchangers, it can be said that more energy is saved in an energy efficiency system with post-wash heat exchanger and mixed wastewater disposal. But in this case, the temperature of the water entering the heat pump is lower than in the case of a separate sewerage outlet.

5. PROSPECTS FOR THE DEVELOPMENT OF THE ENERGY EFFICIENCY SYSTEM

This paper describes only one small part of the possible improvements in the energy efficiency system of laundries. In this work, such a system is laid down, which provides for the introduction of a heat pump system after the heat exchanger. This can significantly reduce the energy required to preheat water for wash cycles. /3,4/

However, increasing the energy efficiency of washing cycles is not the only way to develop this topic. As described above, an increase in the efficiency of ironing cycles, tumble dryer cycles can also be considered. In all these cases, heat exchangers are provided for various design options. Various designs with heat exchangers can be considered, as well as the most efficient types and models of these devices are calculated. /3,4/

However, this is not the only way to optimize such production. In my opinion, another promising direction is the study of the fuel used in boiler houses, the calculation of boiler units and their automation. This leads to lower greenhouse gas emissions resulting from the operation of boilers. In this context, a laundry business that runs on environmentally friendly renewable energy sources can be considered. For example, it could be a laundry room powered by an industrial heat pump. Moreover, during the operation of the heat pump, not only heat is released, but also cooled air is generated, which can be used in the district cooling system or in the air conditioning system of the laundry enterprise itself. /3,4/

The laundry process uses a large amount of detergents that pollute the environment, however, these substances, with the right filtration system, can be quite effectively removed from the water, which can be recycled into washing cycles. Therefore, by designing a good enough filtration system, a closed cycle laundry facility can be created, which will not only help to reduce the cost of washing water, which will seriously affect the energy efficiency of the facility, but also help to reduce the negative impact of the facility on the environment. /3,4/

Automation of laundry processes is also a promising idea to reduce energy consumption in the process of washing, ironing and drying clothes. /3,4/

6. CONCLUSION

The most promising option was the use of an air-to-air heat exchanger after the dryer. This will make it possible to make energy consumption significantly less, this will positively affect the cost of production. Another indisputable advantage is the reduction of thermal pollution of the environment as a result of the utilization of excess heat.

Summarizing all of the above, we can draw some conclusions. A thorough analysis of the laundry of the enterprise allowed us to find places in the production cycle where the enterprise does not operate efficiently and has a lot of unused heat. Based on this, several systems for improving energy efficiency have been proposed. The main objective of the project at this stage was to identify the most optimal energy efficiency scheme. The comparison criterion was the amount of energy saved annually. In the work, three schematic diagrams were compared. The most promising system has shown itself, with a heat exchanger used after the dryer.

The results of the study will be implemented in a real enterprise. This work will be used to improve the energy efficiency of the laundry. In addition to economic benefits, this project optimizes energy consumption, thereby improving the environmental situation.

The topic of further research will be the study of the joint use of heat exchanger systems and a gas boiler. This choice is due to the fact that the enterprise is located in the Leningrad region, which has cheap energy resources necessary for the boiler house.

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LIST OF FIGURES

LIST OF TABLES

№	Name of machines
1	Clock washing machine. LT 50-16
2	Press LP 572
3	Ironing roller D803G
4	Drying mashines

NL-3959 BA Overberg
T +31 (0)343 481580
info@wspsystems.com
www.wspsystems.com

	Date	Name
Drawn	23-7-2016	SD
Checked		
Plot	23-7-2016	

Dimensions in mm

Remarks
SALES LAYOUT

Dimensional tolerances according to EN-ISO 13920BF & ISO 2768-mK

Rev	Changes	Date	Name

Customer Sekunda Russia

Cust. no. 3010 Proj. no. 16-2639

Size A1

Scale 1:100

Ground floor

Drawing number | Revision | Page 001