Influence of Water Scale on Thermal Flow Losses of Domestic Appliances

D. Dobersek, D. Goricanec

Abstract - Research results of how the precipitated water scale on heaters of small domestic appliances influences the consumption of electricity are presented. It shows that the majority of water scale samples are composed of aragonite, calcite and dolomite and that those components have an extraordinary low thermal conductivity. Also, the results show that at 2 mm thick deposit, depending on the chemical composition of water scale, the thermal flow is reduced for 10% to 40%; consequently, the consumption of electricity significantly increases.

Key words – Electricity, heat transfer, heat flow, heat exchanger, water scale

I. INTRODUCTION

DUE to increased consumption of drinking and industrial water the whole world is intensively struggling to find new ways of assuring suitable amounts of water of appropriate quality and according to one of the world's most important thinking how to use energy most efficiently it is reasonable to search the solution for reduction of scale problems [1], [2].

The research is limited to industrial waters which contain a set of dissolved organic and inorganic matters, earths and sands. Larger particles are usually dived with separation methods of mechanical nature. But there is still a problem with dissolved substances in water which, together with microbiological and corrosion products, precipitate in the shape of water scale [3].

These in water dissolved mineral substances that precipitate on walls of flowing water supply systems, on washing machine heaters, in boilers and in dishwashers in a shape of hard linings, cause large technological and economic problems, such as [4], [5]:

- hindering of water flux in pipes causing eventual congestion;
- reduction of the working volume in heat exchangers and impediment of heat transition;
- a more frequent need for maintenance works;
- a premature replacement of devices.

Also due to low thermal conductivity of water scale components these linings represent an insulating layer.

Additionally, research results of impacts of the above-mentioned deposits on thermal transfer reductions for different heat exchangers in households are given, in connection with increased electricity consumption.

II. DRINKING WATER

Drinking waters have, depending on their source (ground water, river water, lake or sea water), and also on the season and the ground over and through which they flow, very different compositions and contents of dissolved substances. Beside ions of hardness (Ca^{2+}, Mg^{2+}) waters could contain other cations (Fe^{2+}, Na^{+}, K^{+}) and different amounts of anions (Cl^{-}, $SO_4{}^{2-}$, NO_3^{-}, HCO_3^{-}) [6].

Mainly calcium and magnesium ions influence on the water hardness. The more ions there are dissolved from earth and rocks the hardest the water. Very hard water could be expected in the areas composed of limestone. Water that springs in the areas composed of other rocks and a bit disintegrated silicates is soft just like rainwater.

The classification of water depending on hardness is given in Table I [7].

Water hardness is very different in Slovenia due to various ground compositions. The water is very hard in the area of Kras and at the seaside because of limestone ground. In the area of Pohorje there are mainly old rocks, therefore the water is soft, and in towns of Ljubljana and Maribor the water is middle hard.

TABLE I
WATER HARDNESS IN GERMAN DEGREES

Water classification	Hardness
Very soft water	0 – 4°n
Soft water	4 – 8°n
Middle hard water	8 – 12°n
Pretty hard water	12 – 18°n
Hard water	18 – 30°n
Very hard water	> 30°n

III. WATER SCALE

Water scale precipitation is a serious problem in many industrial processes as well in the households, literally everywhere where natural water is used. Supplying waters are usually oversaturated with calcium carbonate. The conditions of over saturation are very often achieved during the operation and that is why the water scale precipitates on heat transfer surfaces in cold water systems as well as in high temperature systems [8].

Manuscript received February 6, 2007; Revised Received April 15, 2007
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A. Precipitation

Scale deposits are mainly composed from calcium carbonate.

In natural waters calcium is presented in ionic form Ca^{2+}. Ca^{2+} is led to the water as a result of chemical decomposition of calcareous minerals. Ca^{2+} and CO_3^{2-} ions are always present in natural water. CO_2 from the air is dissolving in water, where a weak carbonic acid is formed [9].

$$CO_2 + H_2O \leftrightarrow H_2CO_3. \qquad (1)$$

Formed acid than dissociates in two steps:

$$H_2CO_3 \Leftrightarrow H^+ + HCO_3^- \qquad (2)$$

$$HCO_3^- \Leftrightarrow H^+ + CO_3^{2-} \qquad (3)$$

Carbonate ions react with Ca^{2+} ions and a very slightly soluble calcium carbonate precipitated, according to equation:

$$Ca(HCO_3)_{2(aq)} \Leftrightarrow CaCO_{3(s)} + CO_{2(g)} + H_2O \qquad (4)$$

If in balance (4) the concentration of CO_2 increase, the balance will moved in left, which means that se $CaCO_3$ will dissolved and pH value will increased. Vice versa by feed the alkalis to the system, the concentration of H^+ will reduces, which means, that balance (2) and (3) will move to the right, more CO_3^{2-} ions will excluded and because of this more solid $CaCO_3$ will precipitated.

$CaCO_3$ starts precipitated, when the concentration of Ca^{2+} ions is larger from equilibrium. In given moment at creation T and pH the solution is oversaturated. In carbonate balance are Ca^{2+}, CO_3^{2-}, H^+, OH^- in HCO_3^- ions.

From the term of solution electroneutrality, that a charge of all present cations is equal to all present anions, the relationship can be written:

$$2 \cdot c_{Ca^{2+}} + c_{H^+} = 2 \cdot c_{CO_3^{2-}} + c_{HCO_3^-} + c_{OH^-} \qquad (5)$$

Considering equations (2), (3) in (5) the relationship for Ca^{2+} concentration in dependence of pH can be written:

$$c_{Ca^{2+}} = \frac{K_w - c^2_{H^+} + \sqrt{(c^2_{H^+} - K_W)^2 + 8K_s \cdot c^2_{H^+} \cdot (2 + \frac{c_{H^+}}{K_2})}}{4c_{H^+}} \qquad (6)$$

The relationship is graphically presented – Fig. 1, from where it is seen that $CaCO_3$ solubility changed with changed temperature. Ta certain value pH solubility starts increasing, because CO_3^{2-} ions occurs.

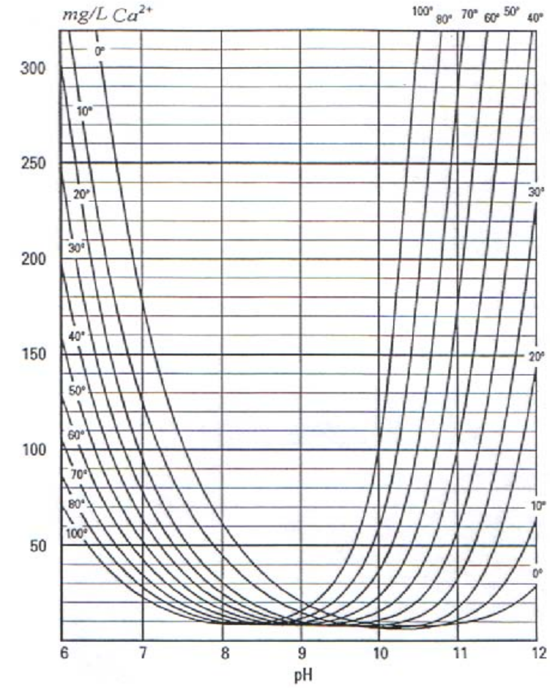

Fig. 1 $CaCO_3$ solubility in ideal solution as a function of pH at certain temperature [9]

If analyse vice versa, it is find that in range pH < 9 solubility falls with increasing temperature. Majority of natural waters are in this range. If pH > 9, the $CaCO_3$ solubility increase with increasing temperature.

B. Crystal structures

The most frequent component of water scale is calcium carbonate, which precipitates in three different forms [10]:

- calcite (Fig.2a)
- aragonite (Fig. 2b)
- vaterite (Fig. 2c).

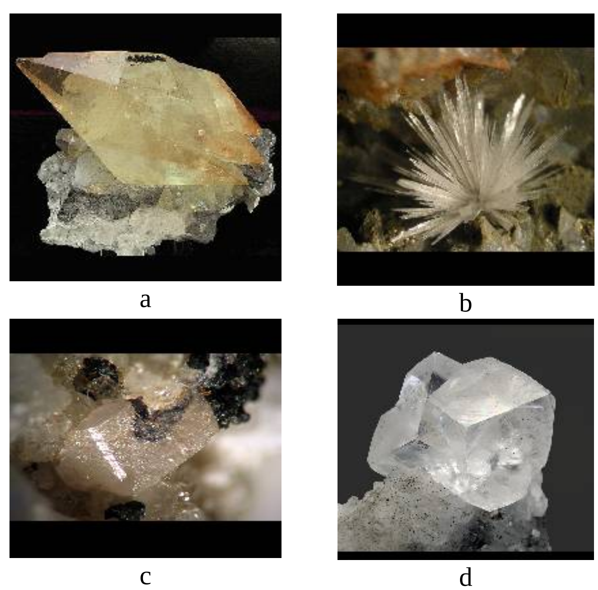

Fig. 2 crystals of calcite (a), aragonite (b), vaterite (c) in dolomite (d) [11]

Their stability is falling round listed order. Very often aragonite precipitated first, more rarely vaterit, which than crystallise into calcite. Fig. 3 presents the solubility of individual calcium carbonate shapes in dependence of temperature.

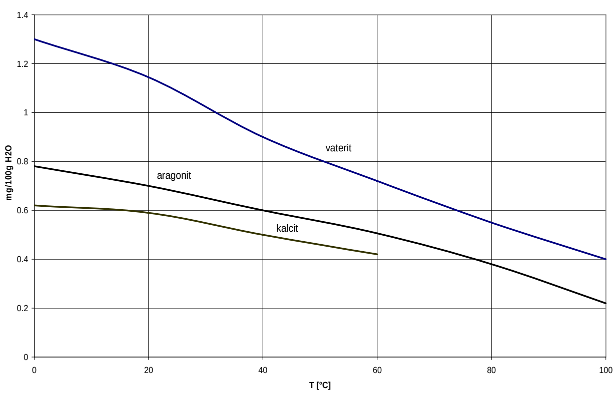

Fig. 3 solubility of different crystal shapes of calcium carbonate

Calcite crystals are usually white or without colours and have a rhombohedra crystal structure. The density of calcite is 2.7 g/cm^3 and its thermal conductivity 2.72 W/mK at 100°C. Rhombohedra crystals have large connection areas and that is why the linings are more compact.

On the other hand we have needles aragonite crystals with smaller contact areas and less compact linings.

Vaterite crystals with hexagonal structure rarely occur and have a density of 2.6 g/cm^3.

Others bivalent ions which are in water usually precipitate in smaller quantities and indirectly effect the precipitation of calcium carbonate.

At the conditions of calcium carbonate precipitation from natural waters the solubility of magnesium carbonate is not exceeded, however Mg^{2+} ions are built into calcite and a new predominant carbonate solid phase of dolomite is formed (Fig. 2 d). Thermal conductivity of dolomite is also very low at 4.78 W/mK at 100°C, and its density is 2.8 g/cm^3.

IV. ELECTRICITY CONSUMPTION OF A SMALL DOMESTIC APPLIANCE

According to statistical data the amount of average electricity consumption in a Slovene household is 290 kWh per month. However, this data do not say enough because the consumption depends on the size of the household, the number of electrical machines and the quality and intensity of their use – as shown in Table II [12].

The use of electricity of electrical boiler for warm water or washing machine and dishwasher could rise due to water scale deposit on heat exchangers. The amount of exceeded water scale depends on water composition, operational temperature and the type and roughness of the material.

TABLE II
ANNUAL ELECTRICITY CONSUMPTION OF A SMALL DOMESTIC APPLIANCE

Domestic appliance	Electricity use per household (kWh/year)
Electrical boiler	1080
Washing machine	300
Dishwasher	410
Dryer	150
Electrical kitchen-range	600
Refrigerator and freezer	960
Lights	310

V. REDUCED HEAT TRANSFER BECAUSE OF THE WATER SCALE

The water scale formed on the surfaces of heat exchangers has very low heat conductivity, it reduces the flow capacity and heat exchange efficiency, leading to a higher investment, operation and maintenance costs.

Two types of heat exchangers are used in practice for heat transfer in water [13]:

- plate heat exchanger,
- pipe heat exchanger.

A. *Plate heat exchanger*

If the heat exchanger is described as a flat wall with area A (Fig. 3), then the heat flow intensity is determined by equation (7) and equation (8) respectively:

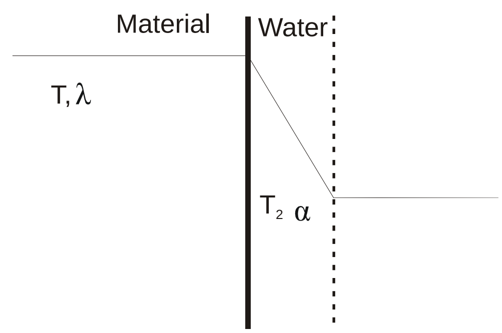

Fig. 3 the temperature curve through the heat exchanger wall

$$\frac{\dot{Q}}{A} = \frac{\Delta T}{\frac{1}{\alpha} + \frac{\delta_1}{\lambda_1}} \,. \tag{7}$$

$$\frac{\dot{Q}}{A} = k \cdot \Delta T \,. \tag{8}$$

Where:

Q heat flow

A heat exchanger area

ΔT temperature difference
α heat conversion
δ_1 heat exchanger wall thickness
λ_1 heat conductivity
k heat transition

The water scale on heat exchanger (Fig. 4) reduces the heat transfer that is why equations (7) and (8) become equations (9) and (10):

$$\frac{\dot{Q}}{A} = \frac{\Delta T}{\frac{1}{\alpha} + \frac{\delta_2}{\lambda_2} + \frac{\delta_1}{\lambda_1}} . \tag{9}$$

$$\frac{\dot{Q}^*}{A} = k^* \cdot \Delta T . \tag{10}$$

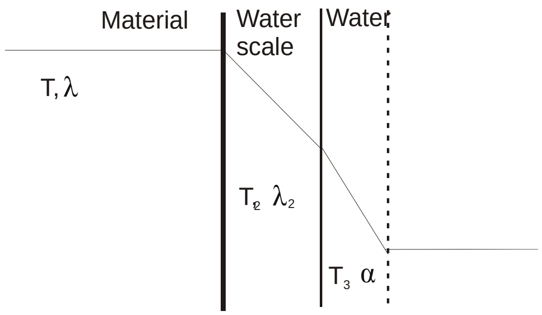

Fig. 4 the temperature curve through the heat exchanger wall and water scale

With the equations (7) and (9) the equation (11) can be written which enables the calculation of heat transfer drop ξ, because of water scale linings:

$$\xi = \frac{Q - Q^*}{Q} = 1 - \frac{k^*}{k} = 1 - \frac{\frac{1}{\alpha} + \frac{\delta_1}{\lambda_1}}{\frac{1}{\alpha} + \frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2}} . \tag{11}$$

B. Pipe heat exchanger

If the heat exchanger has the shape of a pipe with inner diameter r_n (Fig. 5), then the heat flow through the pipe wall is given with the following equation (12):

$$Q = \frac{2\pi L \Delta T}{\frac{1}{\alpha r_2} + \frac{\ln r_2/r_1}{\lambda_m}} . \tag{12}$$

Where:
L pipe length
r_2 external pipe diameter
r_1 internal pipe diameter

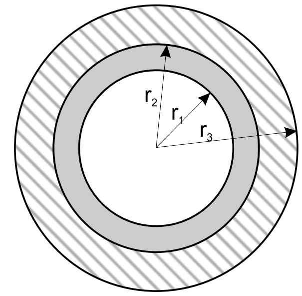

Fig. 6 pipe heat exchanger

Because water scale reduces heat transfer the equation (12) becomes equation (13):

$$Q = \frac{2\pi L \Delta T}{\frac{1}{\alpha r_3} + \frac{\ln r_2/r_1}{\lambda_m} + \frac{\ln r_3/r_2}{\lambda_K}} . \tag{13}$$

With the use of equations (12) and (13) equation (14) can be written which enables the calculation of heat transfer drop ξ:

$$\xi = \frac{Q - Q^*}{Q} = 1 - \frac{k^*}{k} = 1 - \frac{\frac{\lambda_2}{r_2} + \alpha \ln r_2/r_1}{\frac{\lambda_2}{r_3} + \frac{\alpha\lambda_2}{\lambda_3}\ln r_3/r_2 + \alpha \ln r_2/r_1} . \tag{14}$$

C. Heat losses caused by the composition of linings

With the view of investigating the phenomena of scale formation, the causes of intensity of scale precipitation on washing machine heaters and on heaters of boilers for hot water at different operating conditions were examined. Crucial parameters for the conducted experiments were water hardness, the temperature of operation. On Fig. 7 heaters from washing machine are presented after 300 cycles of washing at 60°C and 95°C without washing powders.

a **b**

Fig. 7 washing machine heaters after 300 cycles of washing without washing powders (**a** – at 60°C, **b** – at 95°C)

On Fig. 8 the outlet pipes from the boiler for hot water after 14 days continuous run are presented.

Fig. 8 the outlet pipes from the boiler for hot water

To evaluate the heat transfer reduction caused by water scale linings, the chemical structure of linings and the material of heat exchanger have to be known. Most often the materials used for heat exchangers are [14]:

- copper with thermal conductivity of 395 W/mK;
- stainless steal with thermal conductivity of 26 W/mK.

Thermal conductivity values for components which most often occur in water scale are given in table III.

TABLE III
THERMAL CONDUCTIVITIES OF WATER SCALE COMPONENTS

Component	Thermal conductivity
Aragonite	2.37 W/mK
Calcite	2.72 W/mK
Dolomite	4.78 W/mK
Fur	1.2 W/mK

The data needed for the calculation of reduced thermal efficiency caused by water scale linings, for the example from chapter A. are:

- convection coefficient 500 W/m^{2}K; and
- heat exchanger thickness 3mm.

Values of thermal flow reduction for two different heat exchangers from different materials are given in figures 5 to 8.

The data for calculation of reduced thermal efficiency due to deposit of water scale for the case from chapter B. are:

- convection coefficient 500 W/m^{2}K;
- internal pipe diameter 10 mm;
- external pipe diameter 13 mm.

The use of electricity depending on water scale thickness, in relation to the chemical structure of deposit and the type of heat exchanger, is calculated on the basis of values from Fig. 9 to 12. Results are given in Fig. 13 to 15.

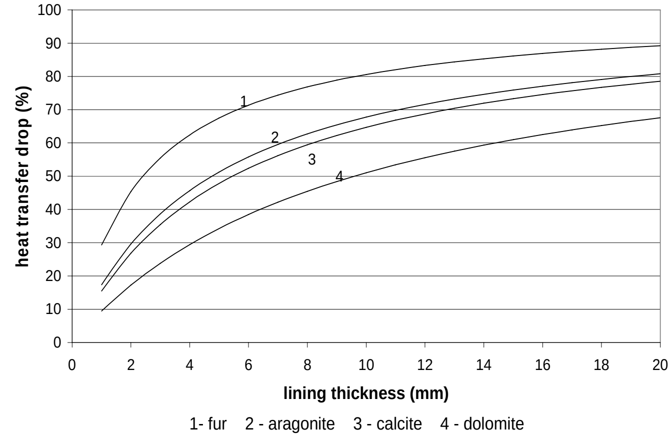

Fig. 9 Heat transfer through copper plate heat exchanger

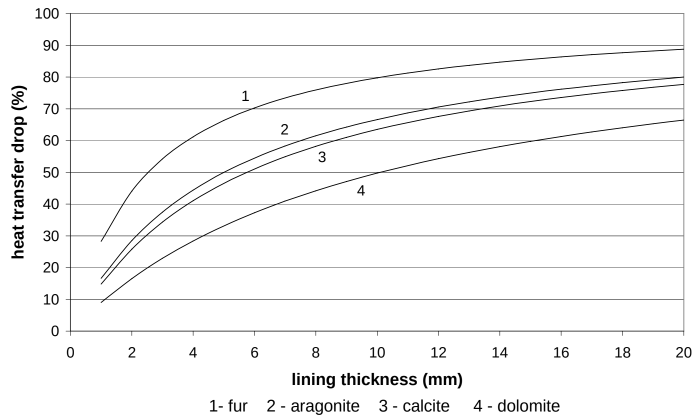

Fig. 10 Heat transfer through stainless steal plate heat exchanger

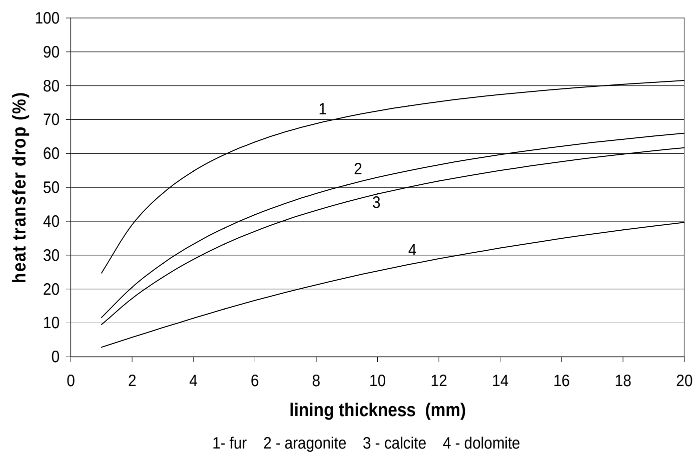

Fig. 11 Heat transfer through the copper pipe

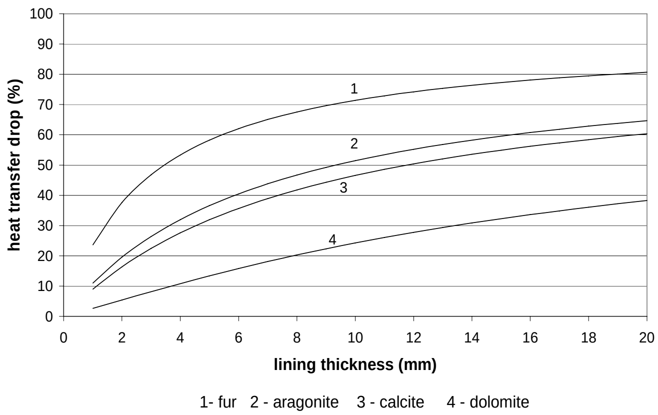

Fig. 12 Heat transfer through the stainless steal pipe

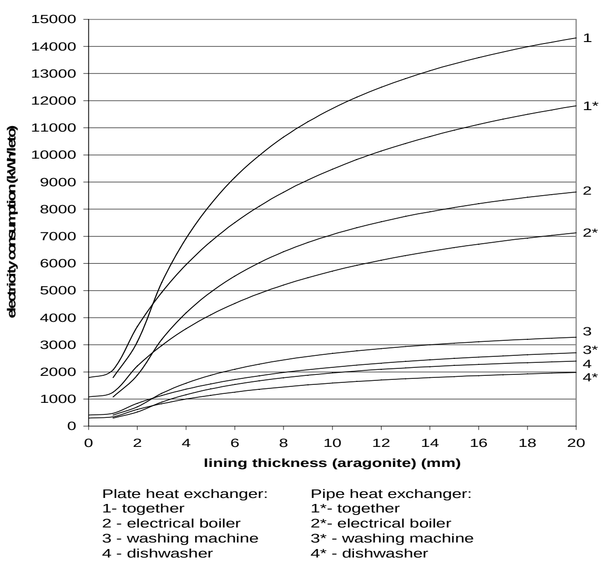

Fig. 13 Electricity consumption for plate and pipe heat exchanger in the case of aragonite

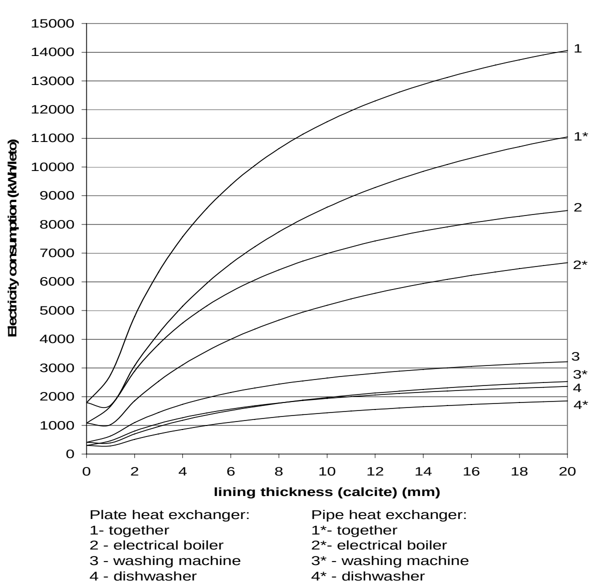

Fig. 14 Electricity consumption for plate and pipe heat exchanger in the case of calcite

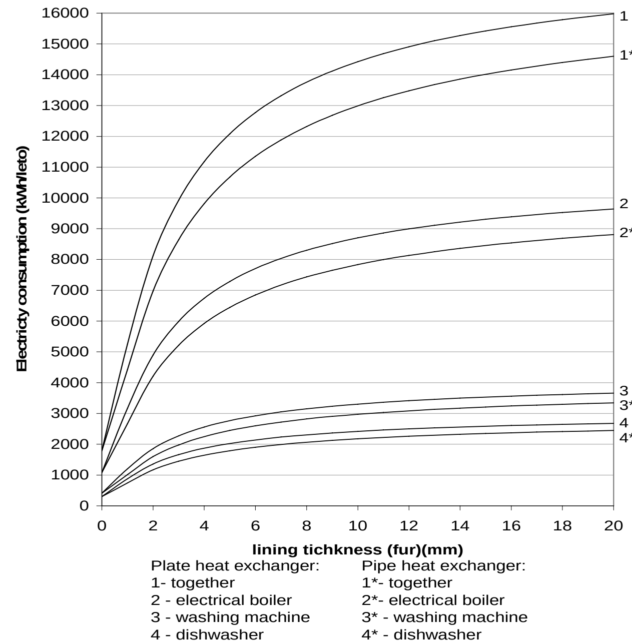

Fig. 15 Electricity consumption for plate and pipe heat exchanger in the case of fur

VI. DISCUSSION AND CONCLUSION

Water scale causes a lot of problems of heat transfer due to its extremely low thermal conductivity. Water scale is most frequently composed of dolomite and calcium carbonate, which precipitate as calcite and aragonite. Rarely calcium sulphate and magnesium carbonate precipitate. A common name for above-mentioned components is fur, which has a thermal conductivity of 1.2 W/mK.

From the Figures 10 to 13 it can be seen how the lining of water scale reduces heat transfer. If the linings are around 3 mm thick, the heat transfer is reduced for 25% to 60%, in the case of a plate heat exchanger, made from cooper or stainless steal.

A bit better results are achieved for pipe heat exchangers where at the same thickness the heat transfer is reduced for 10% to 50%.

Through the research the amount of precipitated water scale on heat exchangers of washing machine and boiler was measured. It was found out that after 300 washing cycles in washing machine at 95°C the linings are 15 mm thick. Linings were thinner in the boiler and dishwasher, and were 3 to 5 mm thick in average.

If we assume that each of the 670,000 households in Slovenia has one washing machine, one boiler and one dishwasher, then around 10000kWh more of electricity will be used per year due to water scale precipitation. The electrical boiler will in average use 6000 to 8000 kWh of electricity per household per year, washing machine 1000 to 1100 kWh/household/year, and dishwasher 1500 do 1700 kWh/household/year.

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