ANALYSIS OF HEAT EXCHANGE PROCESSES IN THE HOT WATER DISTRIBUTION SYSTEMS DURING ITS INTERRUPTED OPERATION

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Abstract
The energy efficiency of the hot water distribution systems is not only affected by heat losses but also by other factors. This contribution points out the concrete amount of energy savings, calculated per 1 m of pipeline length in the insulated pipelines, in comparison to the uninsulated pipelines of small dimensions (DN 15 - DN 32) which are in the distribution networks. Using of numerical simulation in ANSYS_CFX is evident in the part dedicated to the analysis of heat exchange processes. In the last part, energy savings, which can be achieved by the interrupted operation of such systems, are calculated.

Keywords: hot water distribution system, heat losses, finite volume modelling, energy savings

1 Introduction
There is the effort to reduce the energy requirements for the preparation and distribution of hot water (HW) at presently increasing prices of energy**.** The basis for the effective operation of the HW distribution systems is to minimize heat loss in the pipelines. These heat losses in the insulated and also the uninsulated pipes can be calculated from the known relations of heat transfer for the simple and the composed cylindrical [1-5].
During the operation of water or steam pipelines, there is a continuous process of heat insulation destruction. This causes the increased heat losses to the environment what causes in turn the increased operating costs for network operator. Heat losses costs can be reduced by improving cover and thermal insulation of pipelines or total modification of the network including the replacement of pipelines, the diameter adjustment to the current flows and the pipe route optimization. However this enterprise requires the specified investment expenditures [5-7].
Optimizing the work of the HW distribution systems is possible from the point of view the optimum insulation thickness of pipes used in heating pipeline networks. In the first step, optimum pipe diameter is calculated by minimizing the sum of the pipe investment cost and operation cost due to friction without considering the heat losses. In the second step, the optimum insulation thickness is calculated by considering the heat loss and insulation investment cost for the already determined pipe outside diameter. [8-12].
The second method of optimization is the minimization of the total cost, which includes investment for piping and insulation, and operating costs due to pressure and heat losses. [10, 13].

Third method involves a trade off between thermal and fluid flow for the optimum pipe sizing based on minimization of entropy generation without considering cost. Minimum entropy generation or maximum exergy efficiency determines the pipe diameter and insulation thickness. [10, 14]
The fourth method is an extension of the third method, which includes total cost of operation and investment in the optimization. Exergy destruction due to friction and exergy loss due to heat losses are considered as the operation cost while the piping and insulation costs count as investment. Using a similar method, which is in [13] carried out an optimization study on economic sizing of steam piping and insulation based on the available energy cost. [10, 13]
In the paper, we discuss the optimization of the operation of the hot water distribution system by interrupting the circulation of hot water when cooling of pipes occurs. During the examination, we consider time of cooling of thermally insulated and uninsulated pipes of particular diameters. The assessed energy is saved during the period of not supplying the heat to the system as well as energy for reheating of the system to the operating values.
For the evaluation of energy efficiency in the distribution system, two operation modes will be compared. The first one will be the uninterrupted operation when HW is circulating even at the time of zero take-off and, subsequently, the uninterrupted operation when HW is not taken off from the system and HW is not circulating at the time of zero take-off.

2 Experimental methodology

The interrupted circulation of hot water at the time of zero take-off in the pipeline with the thermal insulation

When the circulation of HW is interrupted, the state is non-stationary. Therefore, in this case, it is necessary to determine the temperature of water after a period of cooling - formulae (1) and (2) [15, 16]. The calculation is performed for the pipe segments of the same flow conditions.
The calculation condition is that water in the pipelines is motionless (water is not circulating and the system is without take-off of water). To determine the temperature of water, it is necessary to determine the value of resistance of a segment and the mean specific capacity of a segment - formula (3). The resulting capacity is dependent on the product of the weight and the capacity of water, the pipelines and the thermal insulation in the segment. The same procedure is applied to the circulation pipeline. To determine the total heat required to heat water to the original temperature, the following formula is valid (4).
After random time of cooling, the temperature of HW in the pipeline may be determined from the formula:

$$T_{p2,i} = T_{ea,i} + \left(T_{p1,i} - T_{ea,i}\right) \cdot e^{-\omega} \qquad \text{[K]} \qquad (1)$$

where as the exponent ω will be expressed by the formula:

$$\omega = \frac{1}{R_{lp,i}} \cdot \frac{L_{p,i} \cdot \tau_{\text{int}}}{M_{p,i} \cdot c_{p,i}} \qquad \text{[-]} \qquad (2)$$

where:

$T_{p1,i}$ - mean temperature of HW in the i^{th} segment before start of cooling [K]

$T_{p2,i}$ - mean temperature of HW in the i^{th} segment during given time of cooling [K]
$T_{ea,i}$ - HW pipe the i^{th} segment's surrounding atmosphere temperature [K]
$R_{lp,i}$ - heat resistance of the i^{th} segment of the pipe (m.K.W^{-1})
$L_{p,i}$ - the i^{th} segment's length of HW pipe [m]
τ_{int} - period of interruption of HW circulation [s]
$M_{p,i}$ - total mass of the i^{th} segment of the pipe is equal to the sum of HW, the pipe mass and the thermal insulation mass [kg]
$c_{p,i}$ - mean specific heat of water in the i^{th} segment [J.kg^{-1}.K^{-1}]

$$c_{p,i} = \frac{M_{rp,i} \cdot c_{rp,i} + M_{izp,i} \cdot c_{izp,i} + M_{hw,i} \cdot c_{hw,i}}{M_{p,i}} \qquad [J.kg^{-1}.K^{-1}] \qquad (3)$$

where :
$M_{rp,i}$ - total mass of feed pipe in the i^{th} segment [kg]
$M_{izp,i}$ - total mass of thermal insulation in the i^{th} segment [kg]
$M_{hw,i}$ - total mass of HW in the i^{th} segment [kg]
$c_{rp,i}$ - mean specific heat of feed pipe in the i^{th} segment [J.kg^{-1}.K^{-1}]
$c_{izp,i}$ - mean specific heat of thermal insulation in the i^{th} segment [J.kg^{-1}.K^{-1}]
$c_{hw,i}$ - mean specific heat of HW in the i^{th} segment [J.kg^{-1}.K^{-1}]

To determine the total amount of heat transferred from the water distribution system into the surroundings that is amount of heat needed for heating of HW to ensure the constant operation temperature in the distribution system the formula is valid [15]:

$$Q_2 = \sum_{i=1}^{n}\left[M_{p,i} \cdot c_{p,i} \cdot \left(T_{p1,i} - T_{p2,i}\right)\right] + \sum_{i=1}^{n}\left[M_{c,i} \cdot c_{c,i} \cdot \left(T_{c1,i} - T_{c2,i}\right)\right] \qquad [J] \qquad (4)$$

where:
Q_2 - amount of heat needed to heat HW [J]
$M_{c,i}$ - total mass of the i^{th} segment of circulating pipe is equal to the sum of HW, the pipe mass and the thermal insulation mass [kg]
$c_{c,i}$ - mean specific heat of water in the i^{th} segment [J.kg^{-1}.K^{-1}]
$T_{c1,i}$ - mean temperature of hot water in the i^{th} segment of circulating pipe before start of cooling [K]
$T_{c2,i}$ - mean temperature of hot water in the i^{th} segment of circulating pipe during given time of cooling [K]

Calculation of the temperature of water during the cooling of uninsulated pipeline
Assuming that the heat transfer coefficient on the inner side of the pipe is a few times higher than the coefficient on the outer side, it is possible to neglect the convective thermal resistance in the pipe altogether with the conductive thermal flux of the steel pipe. Then it is valid that the temperature of the pipe and water is the same in its entire volume. From the equilibrium of energy fluxes between the heat flux transferring from the surface of the pipe and the decreases of thermal energy in accordance with the calorimetric equation, the differential equation in the form can be written:

$$\pi \cdot D_{2,i} \cdot L_{p,i} \cdot \alpha_{2,i} \cdot \left(t_{\mathrm{p,i}} - t_{\mathrm{ea,i}}\right) = -\left(\sum M \cdot c\right) \cdot \frac{dt}{d\tau} \quad (5)$$

where:

$D_{2,i}$	- outer diameter of the i[th] segment of pipe	[m]
$\alpha_{2,i}$	- heat transfer coefficient on the outer side of the pipe including free convection and radiation at known surface emissivity	[W.m^{-2}.K^{-1}]
$\sum M \cdot c$	- total heat capacity of the system for: $M_{rp,I}$, $c_{rp,I}$, $M_{hw,I}$, $c_{hw,i}$	[J.K^{-1}]
$t_{p,i}$	- temperature of HW	[°C]
τ	- time	[s]

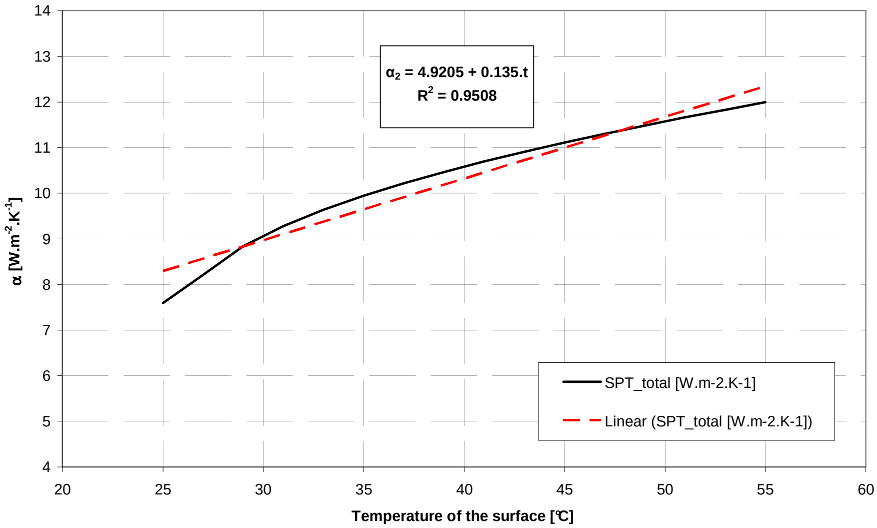

Fig.1 Progression and regression of heat transfer coefficient in the uninsulated pipe DN20

Heat transfer coefficient with consideration of radiant flux at surface emissivity of 0.8 was obtained from the SPT V1.41 software, whereas the dependence of coefficient on the temperature of the pipe surface was constructed in (**Fig. 1**). This dependence can be replaced by linear regression curve, whereas the equation of regression in the form of (6) is used to derive the temperature at the time of τ.

$$\alpha_{2,i} = a + b \cdot t_{p,i} \qquad [\mathrm{W.m^{-2}.K^{-1}}] \quad (6)$$

where a and b are parameters of the regression function.
By combining formulae (5) and (6), the following can be obtained:

$$d\tau = \frac{-\left(\sum M \cdot c\right)}{\pi \cdot D_{2,i} \cdot L_{2,i} \cdot \left(t_{p,i} - t_{ea,i}\right) \cdot \left(a + b \cdot t_{p,i}\right)} \cdot dt \quad (7)$$

By integrating the equation after accepting the boundary conditions, we will obtain the formula for calculating the cooling time.

$$\tau = \frac{k}{a + b \cdot t_{ea,i}} \cdot \ln \frac{(a + b \cdot t_{p,i}) \cdot (t_{p1,i} - t_{ea,i})}{(a + b \cdot t_{p1,i}) \cdot (t_{p,i} - t_{ea,i})} \qquad [s] \qquad (8)$$

where $t_{p1,i}$ is the temperature of water at the beginning of the examined time interval. Parameter k is a substitution which is equal to:

$$k = \frac{\sum M \cdot c}{\pi \cdot D_{2,i} \cdot L_{2,i}} \qquad [J.m^{-2}.K^{-1}] \qquad (9)$$

From equation (8), the calculation of the temperature of HW at the time of τ can be derived:

$$t_{p,i} = \frac{t_{ea,i} \cdot (a + b \cdot t_{p1,i}) \cdot e^{\frac{\tau \cdot (a + b \cdot t_{ea,i})}{k}} + a \cdot (t_{p1,i} - t_{ea,i})}{(a + b \cdot t_{p1,i}) \cdot e^{\frac{\tau \cdot (a + b \cdot t_{ea,i})}{k}} - b \cdot (t_{p1,i} - t_{ea,i})} \qquad [^{o}C] \qquad (10)$$

Use of the finite volume modelling for the analysis of heat exchange processes.

The packages of Computational Fluid Dynamics make it possible to carry out numerical analysis or simulation of processes connected with fluid flow, heat flow processes and other processes [6, 17]. In order to accomplish this work, the finite volume modelling was used [17-20].

For comparison, the numerical simulation of cooling of water was performed in the pipeline by using the ANSYS_CFX software.

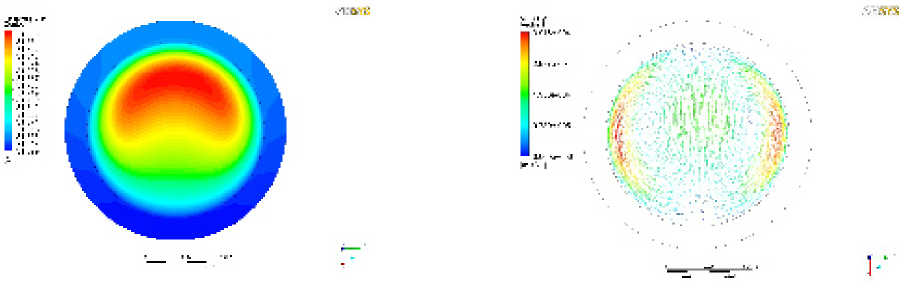

Fig.2 The temperature of cooling and the velocity vector of the DN20 pipe without thermal insulation after 3600 s

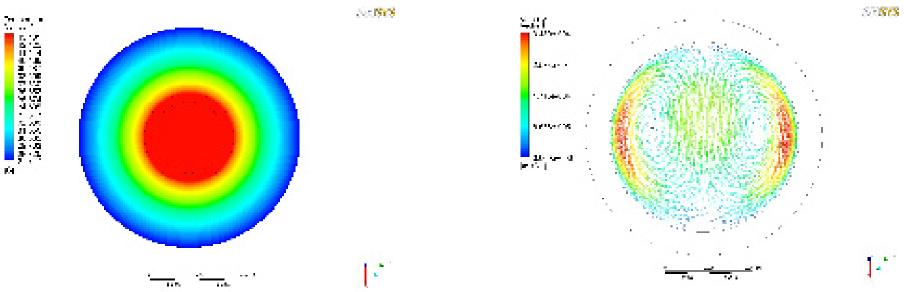

Fig.3 The temperature of cooling and the velocity vector of the DN20 pipe with the thermal insulation of 20 mm after 3600 s, coefficient of thermal conductivity of thermal insulation is λ = 0.04 $W.m^{-1}.K^{-1}$

In the simulation performed by the ANSYS_CFX program, as the boundary condition for the uninsulated pipes was used α – heat transfer for the pipe surroundings that includes free convection and radiation and it is a function of temperature. Initial condition was 52°C - the temperature of the i^{th} segment of the pipe for water. For the insulated pipeline, the initial condition was the temperature of the insulation of 38°C. The laminar model was applied for the simulation.

In the **Fig.2,** there is the temperature progression of cooling of the uninsulated pipe and in the **Fig.3**, there is the temperature progression of cooling of the insulated pipe.

3 Results and discussion

The temperature progression of cooling of the pipes

The uninsulated and the insulated pipes with the thermal insulation of diameters from DN15 to DN32 were analyzed during the interrupted operation. The temperature of water at the beginning of cooling is 52°C and the temperature of the pipe surroundings is 25 °C. The temperature progression of cooling of the uninsulated pipes is shown in **Fig.4.** The temperature progression of cooling of the pipes with the thermal insulation of 20 mm is shown in **Fig.5**.

The temperatures of HW in diagrams in **Fig.4** and **Fig.5** were calculated with the using of the formulae (1), (10).

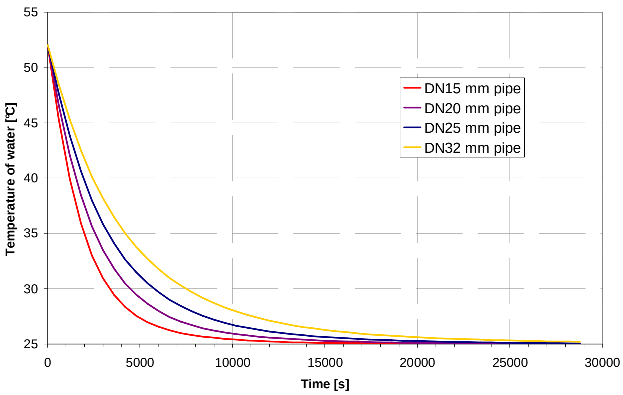

Fig.4 The temperature progression of cooling of the uninsulated pipes from computation

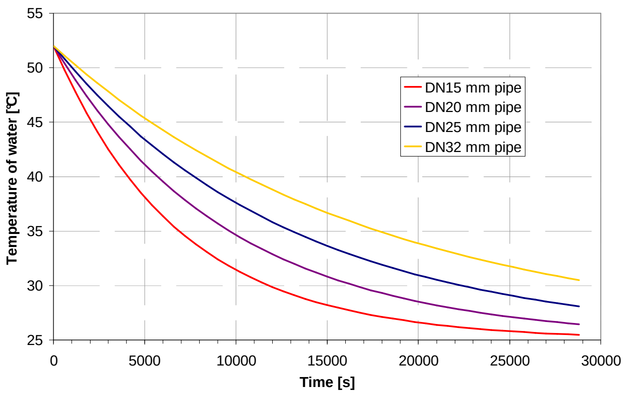

Fig.5 The temperature progression of cooling of the pipes with the thermal insulation of 20 mm (from computation), coefficient of thermal conductivity of thermal insulation is $\lambda = 0.04\ W.m^{-1}.K^{-1}$

The temperature progressions of cooling in **Fig.6** and **Fig.7** are the results of the numerical simulation performed by the ANSYS_CFX program.

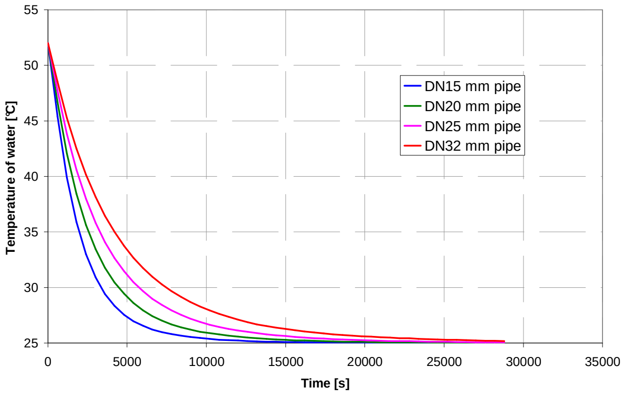

Fig.6 The temperature progression of cooling of the uninsulated pipes which is the result of the numerical simulation

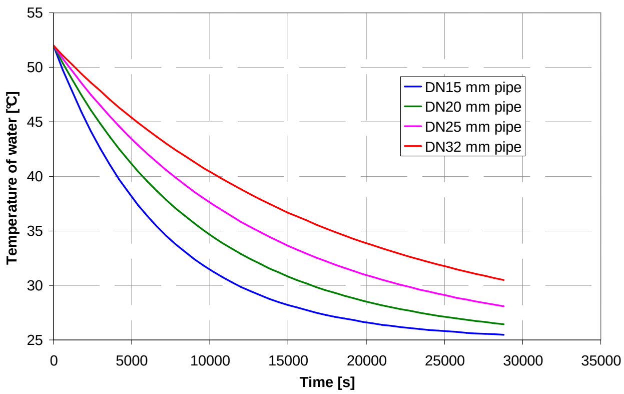

Fig.7 The temperature progression of cooling of the pipes with the thermal insulation of 20 mm, which is the result of the numerical simulation. Coefficient of thermal conductivity of thermal insulation is $\lambda = 0.04$ $W.m^{-1}.K^{-1}$

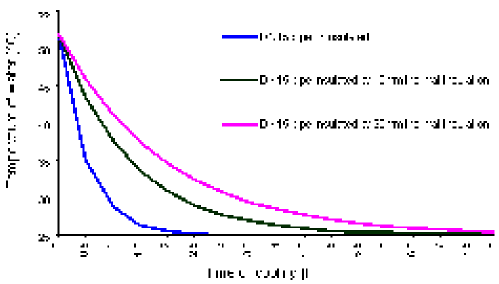

Fig.8 The temperature progression of cooling of the DN15 pipe, coefficient of thermal conductivity of thermal insulation is $\lambda = 0.04$ $W.m^{-1}.K^{-1}$

As it is obvious from the **Fig.4** – **Fig.7**, the calculated progressions of the temperature decrease for the mentioned dimensions of the pipes are equal to the results obtained by the numerical analysis.

Water in the DN15 mm pipe without insulation will be cooled from 52 °C to the temperature of surroundings of 25 °C for 4.5 hours (**Fig.8**), for 6 hours in the DN20 mm pipe, for 7.5 hours in the DN25 mm pipe and for 8.5 hours in the DN32 mm pipe. In the insulated pipes, these periods of cooling are correspondingly longer.

Heat saved by interrupting of hot water circulation

In **Fig.9**, relative amount of heat [%.m^{-1}] saved by interrupting of the operation is shown in the diagram.

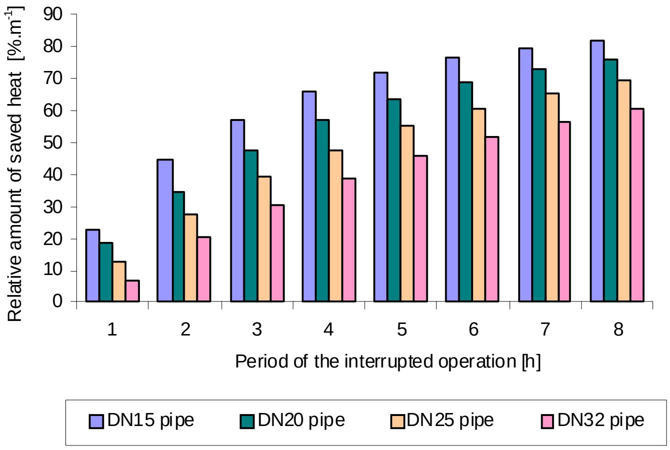

Fig.9 Relative amount of heat saved by interrupting of the operation in the pipe with the thermal insulation of 10 mm after a period of the interrupted operation

At the same period of time, the relative amount of saved heat [%.m^{-1}] is decreasing with the increasing diameter of the pipes. Extending the period of interruption of the operation of the distribution system tends to increase the relative amount of saved heat [%.m^{-1}] for each diameter of the pipe. Percentage contribution of decommission is more significant in the distribution pipelines of lower diameters.

The calculation was performed with the temperature of HW of 52 °C before cooling down. The temperature of surroundings is 25 °C. The segments of the pipeline of 1 m length for DN15, 20, 25 and 32 mm dimensions and the influence of the thermal insulation of 0, 10 and 20 mm were taken into account as the basis for the comparison. The period of the interruption of the circulation is considered to be 1, 2, 3, 4, 5, 6, 7 and 8 hours.

4 Conclusion

By interrupting of the HW supply, the temperature of HW in the pipeline will be decreased. That will result in decreasing of heat losses in the feed and the circulation pipelines and in increasing of energy efficiency of the preparation and the distribution of HW.

The calculation was performed with the temperature of HW of 52 °C before cooling down. The temperature of surroundings is 25 °C. The segments of the pipeline of 1 m length for DN 15, 20, 25 and 32 mm dimensions and the influence of the thermal insulation of 0, 10 and 20 mm were taken into account as the basis for the comparison. The period of the interruption of the circulation is considered to be 1, 2, 3, 4, 5, 6, 7 and 8 hours.

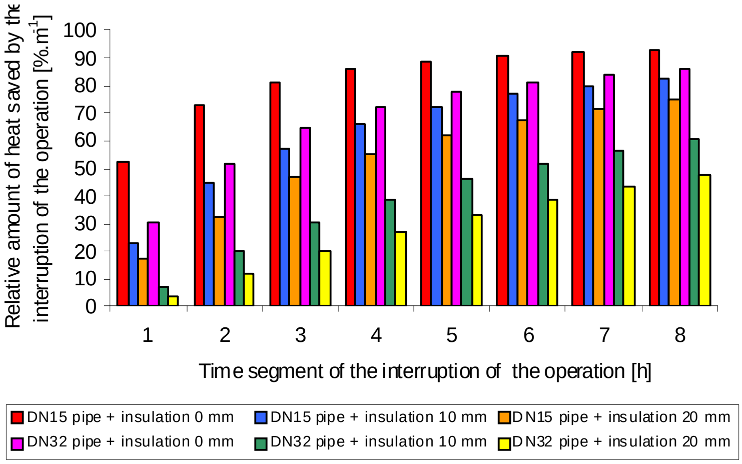

Fig.10 Relative amount of heat saved by the interruption of the operation after a period of cooling in the pipes of DN15 and DN32 diameters

The diagram in **Fig.10** indicates the obvious heat savings during the interruption of the circulation in the pipes without insulation or with insulation. Savings will be reflected mainly in the pipelines of lower diameters. For the interrupted heating of HW without the thermal insulation, the savings are up to 93 % during an eight-hour decommission and the subsequent heating of water to the original temperature for the DN15 pipe. For the DN32 pipes (opposite extreme) with insulation of 20 mm during a one-hour decommission, the savings are only 4 %.
For the pipes without the thermal insulation, the savings appear to be higher, especially, for longer decommissions. The savings are significantly higher in the pipes of smaller diameters which is caused by subsequent need of heating of lower amount of water in the pipe.
The diagrams in **Fig.4** – **Fig.8** point out the cause of the results of the previous cases. Water in the pipe of DN15 diameter, after the interruption of the operation, will be cooled down to the temperature of surroundings of 25 °C for 4.5 hours in the uninsulated pipe. For the pipe of DN32 diameter of 20 mm insulation, after 8 hours of the interruption of the operation, the temperature of water will be decreased to the temperature of 30.07 °C.
The benefit of the interrupting of the circulation, especially, in the pipes of smaller diameters is obvious from the above-mentioned results. The overall proportion of the length of the pipes of smaller diameters to the overall distribution of HW is predominant in the objects. For larger diameters, the effect of the interruption of the operation of the HW distribution system is less significant.

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