Model of non-balanced circulation systems

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Abstract: - Domestic hot water systems of block of flats, built between 1970-90 in Hungary, are installed with circulation systems without hydraulical balance. These systems can guarantee the nominal temperature of domestic hot water only with unrealistically big mass flow of circulation. The most of this mass flow is carried by the nearest risers. The optimal distribution of the circulation mass flow could be realized with correct additional hydraulical balance, but this is difficult on an active system.
We investigated the non-balanced systems with an analytical and a computational model. The analytical model produced simultaneous differential equations; their form was the same as the equations of textile air ducts. We investigated on this model the influence of supply, return and riser diameters. We modelled the pipe system of a non-balanced DHW system for a block of 180 flats with a self-developed computer program to determine the mass flow, pressure and temperature in the system. We present the results of the investigations done with the analytical and computational model.

Key-Words: - domestic hot water circulation; hidraulical balance; computational model; influence of pipe diameter;

1 Introduction

About 472 000 block of flats were built during the years of socialism, between 1965-90 in Hungary. These were built by industrialized building technology. The heating system of almost all flats were connected to a district heating system. In these flats a central domestic hot water (DHW) system was installed usually with an own heat exchanger with DHW storage tank connected in series. According to the regulations the consumer had to tap the determined water temperature (min. 40°C) after at most 1 litre flowed out. Therefore in almost all buildings a DHW circulation system was made. The hydraulical balancing of these circulation systems was not carried out, moreover, the fittings necessary for the balancing were not mounted in either. It is really peculiar because in the 80's in Hungary intensive and successful development was carried out in order to work out a balancing method and fittings for vertical one pipe heating systems. The consumers did not take care of the costs and accordingly they let the cool water flow out to compensate the insufficient temperature of DHW.

At the beginning of the 90's the state price support ceased. The cost of heating and DHW rose suddenly hence the fixed price consumers in large numbers changed to the individual measurement of consumption to reduce these costs. Accordingly, in case of the individual measurement the consumers did not tolerate any longer that the temperature of DHW had to be maintained with flowing out significant amount of cooled water.

It is more difficult to solve caused complaints the non-balanced system as the circulation system is owned by the occupants, while the substation and its part the circulation pump is owned by the heat supplier. The consumers have neither the special knowledge nor the financial resources to solve the problem. Since costs caused by the DHW temperature-complaints and the unsuitable operation of circulation system are imposed on the heat supplier therefore they need to find a suitable solution.

2 Problem formulation

There are several reasons to build and operate reliably the circulation system of a DHW system.

1. Because of comfort respects: without applying circulation in the breaks of consumption the water in the supply pipe of the DHW system will cool down to the temperature, which is unacceptable for the consumer. First and foremost the aim of the circulation system is to ensure the acceptable supplying comfort.
2. Due to energy and water economy respects: if the water in the supply pipe cools down to unacceptable temperature then only the running of water will give reasonable temperature. In case of the running of the water the water and its heat content are both lost. The well-built and properly operated circulation system reduces the loss-costs.
3. Because of hygiene respects: the protection against the Legionella bacteria requires the DHW not to cool down below a certain determined temperature (regulations of several European countries: 55-65°C). The acceptable temperature can be maintained with operating a circulation system or perhaps by using complementary heating.

For sizing the circulation system the German DVGW W533 [1] standard gives instructions. The aim of the circulation is to cover the heat loss of the system, limit the cooling of the hot water until it flows to the consumer. If the allowed cooling of the hot water is Δt and the total heat loss is $\Sigma\dot{Q}$, then the mass flow needed to be circulated in the system is:

$$\dot{m} = \frac{\sum \dot{Q}}{c\Delta t} \qquad (1)$$

The mass flow circulating in the system has to be shared according to the rate of the heat loss of the individual turnouts. Hydraulic balance can set the previously calculated mass flows.

If the hydraulic balance of the circulation system is missing then the system is not able to operate well. Figure 1. represents a system, which supplies DHW for 2564 flats. Without consumption – eg. at night – most of the circulated mass flow turns back at the fore-part of the 1400m long base pipeline. As from the pump in the farther third part of the system there is not any circulation flow in the risers. The nominal consumption leads to similar situation, but in case of this the DHW in the circulation system flows towards the consumer at about from the half part of the base pipeline. This incident results in serious consumer complaints.

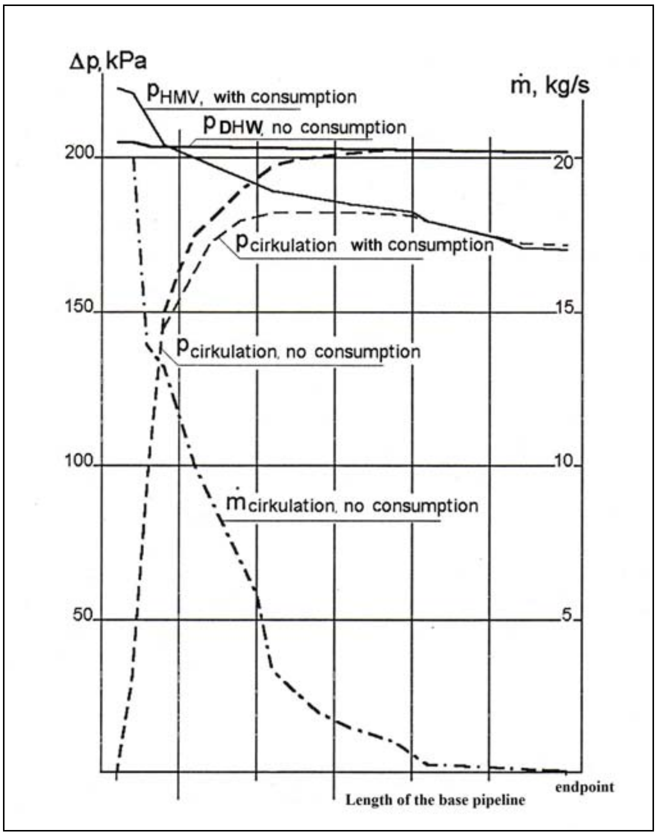

Figure 1.

The incident is similar in smaller systems. Experiments were made to stop the complaints. The following methods were tested in Hungary:

2.1 Changing the circulation pump to a larger one

This is the most often applied method. Effectiveness is limited. In order to enable the consumers who are in an unfavourable condition to get the acceptable circulation mass flow, in the near risers needlessly large mass flow has to be circulated. This energy-wasting solution requires unnecessary pump-work. The high circulation backward temperature destroys the heat transmission conditions of the heat exchanger.

2.2 Increasing the supply temperature

The effect of DHW's increase is small on those sections where is no circulation mass flow. Intensive scale-formation is expected above 60°C due to the Hungarian water-content.

2.3 Using stimulating pump

If there is no acceptable circulation in the risers far from the pump then an additional stimulating pump can stimulate the flow on the critical section. Such experiments were made in several cases without positive results. After building in the stimulating pump, certain – previously free from complaint – consumers had complaints: the temperature of the DHW decreased severely. Figure 2., which was made by computational model, gives the explanation of the incident. Building the stimulating pump into a non-balanced system causes that in a critical section, the pressure of the circulation base pipeline was higher than the pressure of the DHW base pipeline. The consumers which are connected to this section tap the water from the circulation basis pipeline. Certainly this water turned back in the system therefore it cooled down. The situation is the same when the stimulating pump is built into the DHW basis pipeline. The circulation mass flow grows in the risers which are after the stimulating pump, but the temperature of DHW decreases because of the mixing before the pump. Therefore after the pump there is no considerable advance.

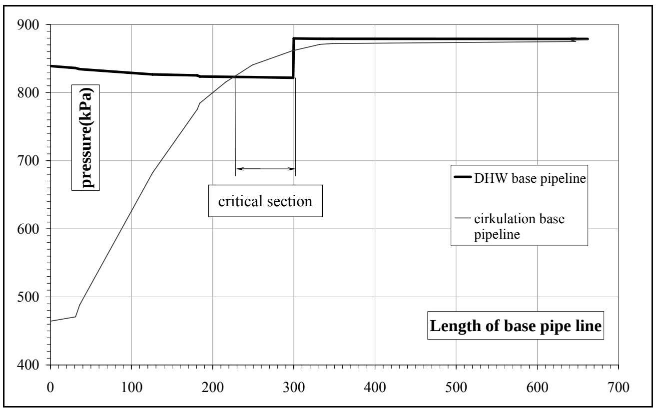

Figure 2.

2.4 Tichelmann-connection

Using the Tichelmann-connection may be the obvious solution to avoid hydraulic balancing. The conditions of usage are: the resistance of the single risers has to be the same, the diameters of the base pipes should fit to each other and to the mass flows. These conditions are not realized in the circulation systems. The diameter of the circulation base pipeline is characteristically less than that of the DHW base pipeline, therefore the hydraulic resistance of the single pipelines will be different after making the joint to Tichelmann-connection.

2.5 Throttle the risers

Basically, avoid the hydraulic balancing causes the problem. Every solution that approximates the single resistance of the circulation circles makes the circulation better.

1. Building in additional balance valves. It is a correct solution but it is rarely used because of its costs and the difficulty of the execution (have to break the working system)
2. Using throttle-sections. Building little diameter sections, which have sized resistance, into the circulation pipe. It was used to replace the balance valves at the beginning of the 90's at some places where there were cheap manpower and pipe-material.
3. Using throttle-discs. Instead of using throttle-sections it is possible to use throttle-discs, particularly if there are rimmed fittings in the circulation pipeline. Sizing of it and the contamination deposited around the throttle-disc cause problems.
4. Using thermostatic mass flow limiting valve. Experiments were made to build in thermostatic mass flow limiters. These are thermostatic valves, which register directly the temperature of the flowing water in the valve. If there is a higher temperature than the preset temperature – eg. if the temperature of the fluid increases on the given riser because of the consumption – the valve closes. If the water cools down the valve opens. These valves were not developed to be used in circulating systems therefore they worked with several deficiency. The valve should have been sized thoroughly and also its K_v value and proportion band should have been fitted to the task. The valve was used without

acceptable sizing in several places in Hungary but most of the usage had some results. Valves with small K_v values built in the risers close to the pump resulted in such a throttle, which made the hydraulic balance of the system better.

5. Using circulation valves. These valves are specifically improved thermostatic mass flow limiting valves for circulation systems. These valves also require correct sizing, if it is left out those problems can be expected that are in heating systems with badly sized thermostatic valves (temperature oscillations, remarkable difference in regulation). It is expected, based on the data of reference books, that the circulation valve will able to solve simply the problems of the circulation system without hydraulic balancing.

3 Model examinations

3.1 The reduced model of non-balanced circulation systems

We made a simple model to examine the phenomena of the non-balanced circulation systems [2]. Put case that the diameter of the supply DHW and the circulation basis pipeline are constant. Similarly put case that the resistance of the loops (which contain the risers of DHW and circulation) are equal. The resistance of the supply pipeline is R_1 , the resistance of the circulation basis pipeline is R_2 . In the present situation the explanation of R_1 and R_2 resistance-factors differ from usual explanations:

$$\Delta p = Rl\dot{V}^2 \tag{2}$$

$$R = \frac{8\lambda\rho}{d^5\pi^2} \tag{3}$$

where

R	resistance-factor
l	length of the section
$\dot{V}$	volumetric flow
λ	pipe-friction factor
ρ	density of the water
d	diameter of the pipe

Since the volumetric flow is variable along the length of the basis pipeline depending on the *x* pipe-length, and the volumetric flow of the forward of DHW and circulating basis pipeline is equal at the same section, the pressure-difference between the forward and circulating basis pipeline is the following :

$$\frac{dp(x)}{dx} = -(R_1 + R_2)\dot{V}^2 \tag{4}$$

Put case that there are innumerable risers between DHW and circulation basis pipeline so that evolves such a plane-flow between the two basis pipelines, which has only the component point from DHW to circulating basis pipeline (there is no transversal flow). In the single section there is *v(x)* specific volumetric flow at pipe-length according to volumetric flow of the risers. The dimension of *v(x)* is m^3/sm. The volumetric flow of the single section depends on the pressure-difference of the basis pipelines:

$$p(x) = rv(x)^2 \tag{5}$$

Where: *r* the resistance-factor expressing the resistance of the plane, which is constant along the basis pipelines due to the equal resistances of the risers.

The value of the volumetric flow is changed due to the flow entering from the basis pipeline into the risers (into the plane between the two basis pipelines, in our model):

$$\frac{d\dot{V}(x)}{dx} = -v(x)\,. \tag{6}$$

The form of these (4)-(6) equations is the same as the equations describing the pressure difference and volume flow of textile air ducts. If we reduce the (4), (5) and (6) equations then the differential-equation for the volumetric flow of the basis pipeline is:

$$\frac{2r}{R_1 + R_2}\dot{V}'(x)\dot{V}''(x) = -\dot{V}(x)^2 \,, \tag{7}$$

the trivial solution of this equation is:

$$\dot{V}(x) = Ae^{-Bx} + C\,. \tag{8}$$

After we put in the border condition $\dot{V}(x=0)=\dot{V}_0$

$$A=\dot{V}_0 \quad (9)$$

$$B=\sqrt[3]{\frac{R_1+R_2}{2r}} \quad (10)$$

$$C=0. \quad (11)$$

The volumetric flow of the basis pipeline, the volumetric flow of the circulation and the pressure along the basis pipeline are:

$$\dot{V}(x)=\dot{V}_0 e^{-\sqrt[3]{\frac{R_1+R_2}{2r}}x} \quad (12)$$

$$v(x)=\dot{V}_0\sqrt[3]{\frac{R_1+R_2}{2r}}e^{-\sqrt[3]{\frac{R_1+R_2}{2r}}x} \quad (13)$$

$$p(x)=\dot{V}_0^2 r^{\frac{1}{3}}\left(\frac{R_1+R_2}{2}\right)^{\frac{2}{3}} e^{-\sqrt[3]{\frac{R_1+R_2}{2r}}x} \quad (14)$$

Some simple conclusions can be drawn from the result (partly they can be determined with speculative method):

1. The mistake of the non-balanced circulation systems is that the volumetric flow on the risers of the first part of the system close to the pump is larger, while on the risers far from the pump it is smaller than the necessary value. This distribution of the circulation mass flow is converse of the desired distribution as the largest mass flow should be in the furthest riser. The distribution of the circulation mass flow can be characterized with the rate of mass flow of the furthest and the nearest risers. At best this rate has to be larger than 1 but in non-balanced circulation systems it will be smaller than 1. This ratio characterizes the goodness of the system, its value put case that the length of the basis pipeline is *L*:

$$\frac{v(L)}{v(0)}=e^{-\sqrt[3]{\frac{R_1+R_2}{2r}}L} \quad (15)$$

The ratio approximates value 1 in case of the smaller length and resistance of the basis pipeline and the larger resistance of the single risers.

The consequence of the statement is that the decrease of the resistance of the basis pipelines (principally by oversizing the circulation basis pipeline) and the undersizing of the circulation risers – or increase of its resistance any kind uniformly – made the hydraulic balance of the system better (according to [3]).

2. If the volumetric flow of the pump which provides the non-balanced system is $\dot{V}_0$ then the pressure-difference needed to the system is:

$$p_0=\dot{V}_0^2 r^{\frac{1}{3}}\left(\frac{R_1+R_2}{2}\right)^{\frac{2}{3}} \quad (16)$$

If we would like to increase the circulation mass flow of the furthest riser by changing the pump and without modifying the resistance of the system (no balancing) then the volumetric flow of the furthest riser will grow in proportion to the other risers, namely the volumetric flow of the close risers, which were unnecessarily large earlier, will proportionally grow as well. The operation point of the system will move away on a resistance-parabola, which gradient is:

$$C=r^{\frac{1}{3}}\left(\frac{R_1+R_2}{2}\right)^{\frac{2}{3}} \quad (17)$$

$$\left(\Delta p=C\dot{V}^2\right)$$

This gradient is determined by the resistance of the base pipelines and the risers. In case of base pipelines having large resistance namely small cross section, the gradient of the parabola is large; because of the pump-changing the increment of the volumetric flow will be small. If the risers and particularly the basis pipelines are oversized then the gradient of the resistance-parabola will be small; therefore by installing a pump with flat characteristic curve it is possible that the increment of the volumetric flow will be significant (Figure 3.) Consequently there is a chance to make better the volumetric flow of the most unfavourable risers only in case of "soft" systems – even then the unnecessary volumetric flow of the close risers will grow.

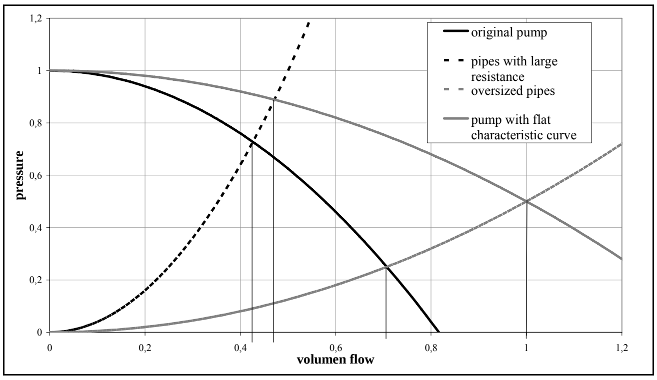

Figure 3.

3. The R_1, R_2 and r resistance-factors are in inverse proportion to the fifth power of the diameter. If the diameter is increased with one size then the resistance-factor will decrease in 2,7÷3,7-fold rate depending on the specific size. If the diameter of any basis pipeline is increased with one size then C resistance-factor of $\Delta p = C\dot{V}^2$ resistance-parabola of the system will increase in 0,74÷0,78 rate; if the size of both basis pipelines is increased with one size then the resistance-factor will decrease to 51%. If the diameters of the risers are increased, then the system will be softer but this does not make the situation better for the unfavourable riser according to the explanation of the 1. point, because the increment of volumetric flow is circulated down on the risers close to the pump. Decreasing the R_1, R_2 resistance-factors leads to the decrease of the r factor at the same time.

3.2 The model-examination of a 180- flat block of flats

In the Department of Building Service Engineering we have been improving a computational program for 20 years called "BORTAVHO" with which looped systems can be modelled from flow and heat technique view. The program uses the method of Almási-Budaváry-Vajna [4] which is an improved Cross-method to determine the volumetric flows in the single line of the loop. The hydraulic and heat-technique data have to be given in detail for the calculation (diameters, length and inside roughness of the pipelines, dynamic loss coefficient; material, quality and thickness of heat insulation; the temperature of the ambience around the pipe, the position of the pipe, flow velocity around the pipe; the character curve of the pump in the system; the places and their volumetric flow where are taken away from the system; etc.); the calculation gives volumetric flows and the heat losses of single sections, the pressures and the temperatures of nodes, etc. as a result.

We modelled the pipe system of a non-balanced DHW system for a 10-storey block of 180 flats. (Figure 4.) The system has 18 circulation risers, the substation is in the centre of the system. The hydraulic balance of the DHW storage tank made the examination more complicated. There was no hydraulic balance in the system and the fittings need for the balance were missing, too. The diameter of the circulation pipelines is DN15 instead of DN20 used in similar houses. The heat insulation of the basis pipelines is not particularly demanding, the insulations of the risers are particularly poor.

The examination showed that if the storage tank is acceptably balanced – not detailed here – then even the non-balanced circulation system can ensure the acceptable temperature of DHW. There are two reasons for this, firstly the circulation pump is oversized and secondly, DN15 sized circulation pipelines have relatively large resistance which equalizes the volumetric flow of the single risers. If there were DN 20 sized circulation risers then there would be serious temperature-complaints in the same system. Instead of balance the unified throttle of the DN20 pipeline makes the distribution of circulation volumetric flow better. In case of DN20 sized risers if the circulation basis pipeline is changed to a larger one that results in small effect. Increasing the diameter of the circulation base pipeline and change the system to Tichelmann-connection results that the temperature of DHW will be acceptable again. It is important that the total resistance of the supply and circulation basis pipelines belonging to single risers can only differ a little.

4 Summary

In the non-balanced DHW circulation systems the additional hydraulic balancing is the most suitable method to stop the complaints. Choosing the right size of the basis pipelines and risers can make the distribution of circulation volumetric flow better. In case of small resistance of basis pipelines and uniformly large resistance of risers the balance with valves can become unnecessary.

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