ENERGY CONSUMED BY VALVES IN CONVENTIONAL WATER SYSTEMS AND THE APPLICATION OF A POWER-DECENTRALIZATION SYSTEM

YONGZHENG FU[1], YAQIAO CAI[1], ZAIPENG ZHANG[1] AND KEQI WU[2]

[1] *Wuhan University of Science and Technology, 199 Xiongchu Street, 430070 Wuhan, People's Republic of China*
fuyongzheng@vip.163.com

[2] *Huazhong University of Science and Technology, Hubei, 430070 Wuhan, People's Republic of China*
hustwja@163.com

(Received 6 June 2006)

Abstract: The power consumption by valves of a conventional (*i.e.* power-centralized) water system is analyzed on the example of a water heating system in order to evaluate the extent of energy savings achievable in a power-decentralized system. The configuration and application of a power-decentralized system is briefly discussed.

Keywords: power-centralized system, power-decentralized system, valves' power consumption, valve

1. Preface

At present, there are several main power types of fluid systems:

- individual pumps;
- parallel connection pumps;
- an additional pump is installed in large water system, in the middle or back part of the network's trunk line, when networks are too long or the system needs to be extended.

These types can be called power-centralized systems, as the energy needed to make the fluid flow in the system is provided by one or two power sources. In these systems (see Figure 1), the pump's head is fixed according to the needs of the most demanding branch. Thus, pressure on other branches would be surplus to what they need; the closer to the power source, the greater the surplus. The extra pressure can only be consumed by increasing the resistance of a branch. Usually, the flow in the most demanding branch is only a small part of the total flow in the system. For the sake of flow in a small part, the flow in other branches has to be pumped to high a potential energy and then valves are used to consume the extra energy, which is a great waste of energy.

A system has been proposed (*cf.* [1], see Figure 4 below) to „use pumps instead of valves", namely that, apart from the main pipe, all branches should have pumps installed so that the pump head of each branch can be adjusted individually and the energy waste be avoided. In this article, such a system is called a power-decentralized system. In contrast to conventional power-centralized systems, this system requires numerous pumps and its management is more complex, so whether it is preferable for a particular project will depend on the relationship between its advantages and disadvantages. In order to make the right choice, we should first determine how much energy can be saved by this system.

The analysis of energy consumption by valves of a power-centralized system is the keystone of this article, which is an attempt to estimate the range of the energy savings achievable in a power-decentralized system. It contains a brief analysis of the configuration and applications of power-decentralized systems, hoping to stimulate further research and practical application of power-decentralized systems.

2. Energy consumption by valves of a conventional system

2.1. Designed working conditions

2.1.1. Simple system

In this article, a water heating system is taken as an example for analysis; other systems could also be analyzed in a similar way. Figure 1 shows a common direct return heating system. It is called a simple system, as every branch has only one user.

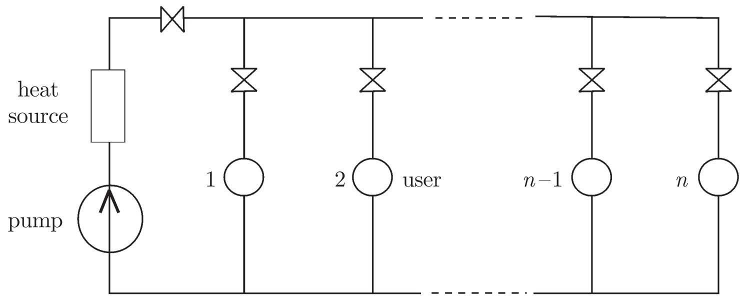

Figure 1. Sketch of a conventional water heating system: simple system

For the sake of convenience, we shall assume that all users are equal in terms of flow and distance (including the distance between the first user and the heat source). Each user shall require equal available pressure (actually, every user has the same pressure drop), and all pipes shall have the same flow resistance per unit length. Ignoring the resistance of fully opened valves and assuming the design to be rational and the pump to be suitable, when the valves of the main pipe and a user are wide open, the user's pressure is simply equal to the pressure difference.

According to principle of energy conservation, the following relationship can be derived:

$$E = E_r + E_p + E_v + E_y, \tag{1}$$

where

E – the pump's output energy, *viz.* the system's energy needs satisfied by the pump,
E_r – the energy consumption of the heat source,
E_p – the energy consumption on the main pipes,
E_v – the total energy consumed by all valves,
E_y – the total energy consumed by all users (in Figure 1, energy consumed by an individual user equals the energy consumed in this branch save for its valve).

According to the hypothesis mentioned above,

$$E_p = \sum_{j=1}^{n} jGH_p = \frac{1}{2}n(n+1)GH_p, \tag{2}$$

where H_p is the total pressure loss of a pair of corresponding main supply and return pipes, [m] (H_p of each pipe section being equal), and G is the flow of each user, [N/s].

Valve's energy consumption of user n is close to zero, that of user $(n-1)$ is $H_p \cdot G$, that of user $(n-2)$ is $H_p \cdot 2G$ and – by analogy – that of user $(n-k)$ is $H_p \cdot kG$. As the first user's energy consumption is $H_p \cdot (n-1)$, the total valve energy consumption of all users is as follows:

$$E_v = \sum_{j=1}^{n} jGH_p = \frac{1}{2}n(n-1)GH_p. \tag{3}$$

If we refer to the energy consumption other than at the heat source and by users as network energy consumption, represented by E_w, it can be expressed as:

$$E_w = E_p + E_v = \frac{1}{2}n(n+1)GH_p + \frac{1}{2}n(n-1)GH_p = n^2 GH_p. \tag{4}$$

The proportion of energy consumed by valves to that consumed by the network is:

$$\alpha_v = \frac{E_v}{E_w} = \frac{\frac{1}{2}n(n-1)GH_p}{n^2 GH_p} = \frac{n-1}{2n}. \tag{5}$$

It is evident that as the number of users increases, α_v approaches 50%.

Energy consumption of the heat source is $E_r = nGH_r$, H_r being the pressure loss at the heat source. Each user's energy consumption of is GH_y, H_y being a consumer's pressure loss, so the total users' energy consumption is $E_y = nGH_y$.

The proportion of valve energy consumption to the total energy consumption (*viz.* the pump's output power) is

$$\beta_v = \frac{E_v}{E_r + E_p + E_v + E_y} = \frac{(n-1)H_p}{2(H_r + H_y + nH_p)}, \tag{6}$$

$$\frac{\partial \beta_v}{\partial n} = \frac{1}{2}\frac{H_p(H_r + H_y + H_p)}{(H_r + H_y + nH_p)^2} > 0. \tag{7}$$

β_v clearly increases with n. According to formula (6), β_v increases as H_p increases, while β_v decreases as H_r and H_y increase.

According to the range of flow resistance per unit length, of pipe and fittings' frictional losses given in [2], if we assume the pipe's pressure loss per unit length (including partial loss) as 90Pa/m and the distance between users (including the distance between the heat source and the first user) as 50m, then $H_p = 90\cdot 50\cdot 2/9800 = 0.9184$m. The pressure loss at the heat source has been taken as 10m, user's pressure loss is 5m, values of α_v and β_v at different n's are listed in Table 1.

Table 1. α_v and β_v at various values of n (in %)

n	5	10	15	20
α_v	40.0	45.0	46.6	47.5
β_v	9.4	17.1	22.3	26.1

2.1.2. Complicated system

As shown in Figure 2, the branch of the main pipe serves several users. As it is much more complicated than the simple system shown in Figure 1, we shall call it a complicated system.

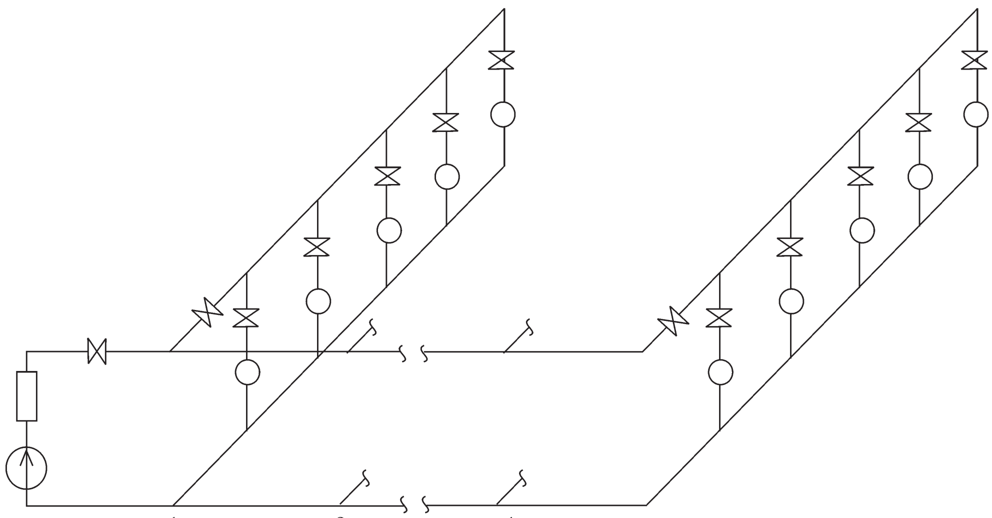

Figure 2. Sketch of a conventional water heating system: complicated system

For the sake of convenience, we shall assume that all the n branches are in the same working condition, each offers heat to n' users, the users are equal in terms of flow and distance, the branches and the main line have the same flow resistance per unit length. We shall also assume that the design is rational and the pump is suitable and that, when the valves of the main branch (and user) at the network's end are wide-open, the end user receives just the pressure that he actually needs. Ignoring the valves' resistance when wide-open, the energy consumption of the main pipe will be:

$$E_{p1} = \frac{1}{2}n(n+1)n'GH_p, \tag{8}$$

where G is the fluid flow of each user, [N/s], and H_p is the total pressure loss of a pair of corresponding main supply and return pipes, [m]. H_p of each pipe section is equal. The energy consumption of the main branch is:

$$E_{p2} = \left[\frac{1}{2}n'(n'+1)GH'_p\right]n = \frac{1}{2}n'(n'+1)nGH'_p, \tag{9}$$

where H_p is the total pressure loss of a pair of corresponding main supply and return main branches, [m].

$$E_p = E_{p1} + E_{p2} = \frac{1}{2}nn'G\left[(n+1)H_p + (n'+1)H'_p\right]. \tag{10}$$

The vales' energy consumption in each branch is:

$$E_{v1} = \frac{1}{2}n(n-1)n'GH_p, \tag{11}$$

the energy consumption of each user is:

$$E_{v2} = \frac{1}{2}n'(n'-1)nGH'_p \tag{12}$$

the total energy consumed by all valves is:

$$E_v = E_{v1} + E_{v2} = \frac{1}{2}nn'G\left[(n-1)H_p + (n'-1)H'_p\right] \tag{13}$$

and the proportion of energy consumption by the valves to the network's energy consumption is:

$$\alpha_v = \frac{E_v}{E_p + E_v} = \frac{(n-1)H_p + (n'-1)H'_p}{2(nH_p + n'H'_p)}, \tag{14}$$

$$\frac{\partial \alpha_v}{\partial n} = \frac{H_p(H_p + H'_p)}{2(nH_p + n'H'_p)^2} > 0, \tag{15}$$

$$\frac{\partial \alpha_v}{\partial n'} = \frac{H'_p(H_p + H'_p)}{2(nH_p + n'H'_p)^2} > 0. \tag{16}$$

Apparently, α_v increases with increasing n and n'. As has been the case in the simple system, α_v cannot exceed 50%.

The proportion of energy consumption of all valves to the total energy consumption is:

$$\beta_v = \frac{E_v}{E_r + E_p + E_v + E_y} = \frac{(n-1)H_p + (n'-1)H'_p}{2(H_r + H_y + nH_p + n'H'_p)}, \tag{17}$$

$$\frac{\partial \beta_v}{\partial n} = \frac{H_p(H_r + H_y + H_p + H'_p)}{2(H_r + H_y + nH_p + n'H'_p)^2} > 0, \tag{18}$$

$$\frac{\partial \beta_v}{\partial n'} = \frac{H'_p(H_r + H_y + H_p + H'_p)}{2(H_r + H_y + nH_p + n'H'_p)^2} > 0. \tag{19}$$

β_v also increases with increasing n and n'; when n and n' increase, the amount of energy consumed by the heat source and users decreases, but the energy consumed by the network increases. At the same time, the proportion of energy consumed by valves to that of the networks approaches 50%.

If the distance between branches is 100m and the pressure loss of main branch per unit length (including the fitting friction loss) is 75Pa/m, then $H_p =$

Table 2. α_v and β_v at various value combinations of n and n' (in %)

n	5	5	5	10	10	10
n'	5	10	20	5	10	20
α_v	40.0	42.7	45.3	43.8	45.0	46.4
β_v	18.0	22.6	28.7	25.0	27.9	32.1

$75\cdot 100\cdot 2/9800 = 1.5306$m. If the distance between users is 50m and the pressure loss of a sub-branch per unit length is 90Pa/m, then $H'_p = 50\cdot 90\cdot 2/9800 = 0.9184$m. Taking the pressure loss at the heat source as $H_r = 10$m and $H_y = 5$m for a user, we obtain values of α_v and β_v as presented in Table 2.

It can be inferred from Table 2 that the energy consumption by valves in a water heating system is considerable. Moreover, the results of Tables 1 and 2 are based on the assumption that the pump's head and flow just meet the requirements, with no margins left. In fact, when calculating the system's pressure loss, it is usually difficult to obtain an accurate result, so when choosing a pump, one makes sure that the pump's head and flow are a slightly in excess of the requirements. When the system is in operation, valves consume the extra energy. Considering this, α_v may exceed 50% and β_v may reach or exceed 1/3 in large or medium systems.

2.2. Regulating working conditions

Many fluid systems should adjust their flow according to their load changes. There are two types of regulation: concentrated regulation and partial regulation.

Concentrated regulation consists in changing the flow of the whole system, while partial regulation is changing the flow of a single branch, user or even a single terminal device. At present, there are three main types of concentrated regulation in practical projects: (a) throttle regulation, (b) variable-speed pump regulation and (c) parallel-connected pumps, regulated by changing their number. Throttle regulation can be achieved by changing the degree of opening the valve in the main pipe. Apparently, throttle regulation increases valves' energy consumption.

The designed working condition is shown in Figure 3 as point 1. Let us suppose that all vales in the main pipe are wide open. By throttle regulation, the working condition is changed to point 2; a vertical line drawn from point 2 intersects system's curve at point 3, the pressure loss of throttle regulation being $H_2 - H_3$, except for the main pipe, where the system's pressure loss is H_3. Then the proportion of all valves' energy consumption to the system's total energy consumption is:

$$\beta_{v_t} = \frac{(H_2 - H_3)G_2 + H_3 G_2 \beta_v}{H_2 G_2} = \frac{H_2 - (1-\beta_v)H_3}{H_2}, \tag{20}$$

where β_v is the proportion of valves' energy consumption to the total energy consumption under designed working condition. Except for the main pipe's resistance change, the distribution of resistances does not change, so the proportion of energy consumed by other valves to the total consumption excluding the main pipe valves will not change.

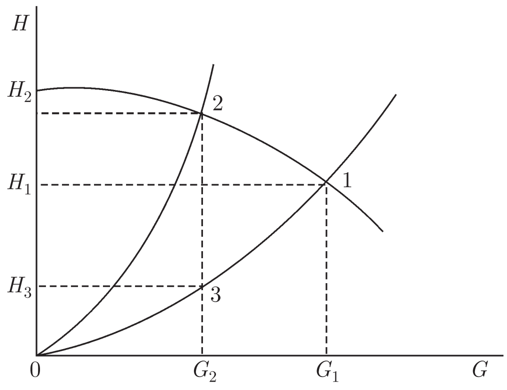

Figure 3. Sketch of throttle regulation in the main pipe

Assuming $\bar{G} = \frac{G_2}{G_1}$, we obtain $H_3 = \bar{G}^2 H_1$. Formula (20) can be expressed as:

$$\beta_{vt} = \frac{(H_2 - H_1) + H_1 - (1-\beta_v)\bar{G}^2 H_1}{(H_2 - H_1) + H_1}, \tag{21}$$

where $H_2 - H_1$ is related to the pumps' characteristics. In order to simplify the analysis, we remove it from formula (21) and obtain the following inequality:

$$\beta_{vt} > \frac{H_1 - (1-\beta_v)\bar{G}^2 H_1}{H_1} = 1 - (1-\beta_v)\bar{G}^2. \tag{22}$$

The right-hand side of Inequality (22) assumes its maximum when the curve of the pump's characteristic is a horizontal line; however, actual pump's curve is always steepper, which is clearly indicated in Figure 3. The proportion of energy consumed by valves to that consumed by the network can be obtained through a similar deduction:

$$\alpha_{vt} > \frac{1 - (1-\beta_v)\bar{G}^2}{1 - (1-\beta_v/\alpha_v)\bar{G}^2}. \tag{23}$$

For the system shown in Figure 1 and according to the conditions given in Subsection 2.1.1, if $n = 20$ under designed working condition, $\alpha_v = 47.5\%$ and $\beta_v = 21.3\%$ are found from Table 1. If throttle regulation is applied in the main pipe to reduce the flow to 80% of its designed value, we can find $\alpha_{vt} > 76.7\%$ and $\beta_{vt} > 49.6\%$ from formulae (22) and (23). Similarly, if the flow drops to 50%, then $\alpha_{vt} > 93.1\%$ and $\beta_{vt} > 80.3\%$. This illustrates the capacity of throttle regulation in the main pipe to increase the quotient of energy consumption. At the same time, the pump's efficiency will be reduced due to the altered working conditions.

Variable-speed pump and changing the number of parallel-connected pumps are method of changing power; the distribution of resistance in the system is not affected, so α_v and β_v will not change in the process. Basically, the efficiency of a closed water cycle system will not change upon changing the pump's speed, but if the number of pumps is changed, its efficiency will be reduced. In other words, although α_v and β_v remain the same, provided that the exported power is the same, the imported power of a changed number of parallel-connected pumps is greater than that of a variable-speed pump.

With regard to power-centralized systems, partial regulation at any place consists in throttle regulation, thus the energy consumed by valves will certainly be increased.

3. Configuration of a power-decentralized system

We have learned from the above analysis and calculations that throttle regulation of a power-centralized system with several branches has a large quotient of energy consumption. When regulating the working conditions, although power-concentrated regulation reduces the energy required by the system, the scale of energy consumed by valves does not change. While concentrated and partial regulation increase energy consumption by valves, power-centralized regulation is the basic cause of such energy consumption. Thus, the best way to reduce, even eliminate, consumption of energy by valves is to change the system's power scheme from power-centralized to power-decentralized. In other words, instead of installing a pump in the main pipe, a pump should be installed in each branch to offer the power actually need there. The power-centralized system in Figure 1 can be changed into a power-decentralized system (see Figure 4) by adding a pump at each branch. When the pumps are chosen properly, the flow distribution will meet the requirements.

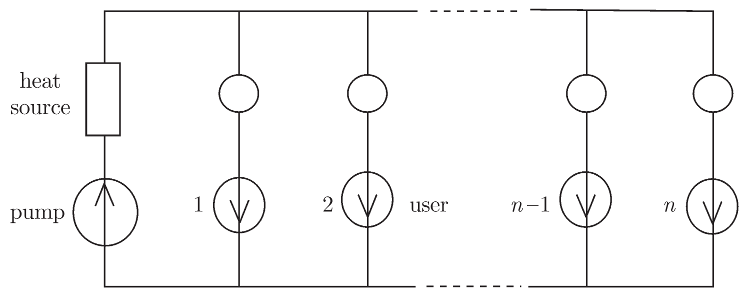

Figure 4. Sketch of a power-decentralized system

With regard to a system whose flow needs to be regulated frequently, the pump in the main cycle and those in the branches should be variable-speed pumps with automatically controlled speed, so that as much power is distributed timely as is needed at each branch. As the flow is regulated and adjusted merely by changing the pumps' speed, there is no need for valves to be installed at the branches. As there are no valves, no energy is consumed by them: a power-decentralized system saves the energy consumed by valves in a power-centralized system.

With regard systems whose flow is fixed during operation, fixed speed pumps may be used. Manually-operated valves should also be installed in branches additionally to the power equipment to enable adjustments correcting unreasonable distribution of the flow due to the system's design or inaccurate calculation or improper choice of power equipment. Such valves will consume some energy, but it will be much less than consumed in a power-centralized system.

Apparently, there is a number of combinations of the main and branch pumps' heads fulfilling a system's needs. For systems with fixed flow, the best combinations are based on the least investment required by the project. With variable-flow systems, stability should also be considered, in order to reduce the interference and mutual influence of branches as much as possible. This will be discussed in detail in a separate article.

For the complicated system shown in Figure 2, there are two methods of conversion into a power-decentralized system: one is to install pumps in the main pipe, sub-branches and users' branches, the other is to install pumps only in the main pipe and sub-branches. The latter would be called a half-power-decentralized system.

4. Application of a power-decentralized system

In theory, any system with several branches can have its flow regulated and distributed according to the power-decentralized method, but considering the complexity of system management and the number of pumps that may be required, adoption of this system will depend on the following principles of economy.

(1) The larger the system, the more energy is consumed by valves in a power-centralized scheme, and the greater the energy savings in a power-decentralized scheme.

(2) Automatic control techniques are more and more common in systems with frequently regulated flow, often with electric valves similar in price to those of variable-speed pumps. Thus, when the power-decentralized method is applied to such systems, it does not increase the costs significantly.

5. Conclusions

(1) The larger the power-centralized system, the greater the proportion of energy consumption by valves to the equipment's output power is. For designed working conditions of a medium-to-large water heating system, the proportion may reach or even exceed 1/3. Concentrated regulation of the main pipe valve's throttle would greatly increase valves' energy consumption. Although a variable-speed pump or a changed number of parallel pumps will reduce the energy required by the system, the scale of energy consumed by valves will not change. Moreover, any partial regulation may increase energy consumption by valves.

(2) In a power-decentralized system, power equipment is installed in the main pipe and in the branches. The flow can be distributed by choosing the pumps' heads. As valves are not used to distribute and adapt the flow, energy consumption by valves is eliminated or greatly reduced.

(3) For a power-decentralized system with variable flow, the pumps in the main pipe and the branches should be automatically-controlled variable-speed pumps, so that the flow is regulated to fulfill the energy needs of each branch by changing the pumps' speed. For, manually-operated valves should also be installed in the branches of a fixed-flow power-decentralized system in addition to power equipment, so as to correct unreasonable flow distribution due to the system's design or inaccurate calculation or improper choice of power equipment.

(4) The larger the system, the more substantial the energy savings offered by a power-decentralized system. For systems with variable flow and automatic control, the costs of electric valves are comparable with those of variable-speed pumps.

Thus, adoption of the power-decentralized method will not significantly increase the project's costs, while saving a large amount of energy that would be consumed by valves.

References

[1] Jiang Y 1997 *Heating Ventilation and Air Conditioning* **27** (2) 66
[2] He P and Sun G 1993 *Heating Engineering*, China Architecture and Building Press, Beijing