The Effect of Flow Balance on the Reduction of Life Cycle Cost in Hydronic Networks

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Hydronic networks transfer energy through the heating and cooling of the working fluid. The heat transfer depends on the temperature and flow rate of the fluid. Even small changes in the physical parameters of the transmission network, such as size, length, and cross-sectional area, can cause changes in the flow rate and transferred heat flux due to the non-linear equations governing the transmission of the working fluid. This research aims to investigate the possibility of balancing energy transmission networks and the cost reduction that results from this balance. The energy transmission network is modeled using the Hardy-Cross method, and the results are analyzed in the 50-year life cycle cost of the network. The research method used is a numerical analysis using the Newton-Raphson method to calculate the current of the energy transmission network through the numerical solution. The research presents a new model for designing industrial and residential energy transmission networks based on the density and layout of the network. The model can reduce energy consumption, air pollution production, and operating costs during the operation period of a complex. This research shows a 30% reduction in the operating costs of the energy transmission network in its balanced condition. The model presented in this research applies to other energy transmission networks and can be used to reduce energy consumption and operating costs.

Keywords: *life cost cycle, hydronic network, flow balance, reduction of water consumption, energy, carbon dioxide.*

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Nomenclature

n	Index of cluster
Q (m^3/s)	flow rate of each consumer
K	Geometrical parameter of distribution network
G (m/s^2)	Gravity constant
L (m)	Pipe length
D (m)	Pipe Diameter
H	Pressure drop
LCC	Life cycle cost
C_t	Total expenses of a system includes initial, and future cost
N	Duration
D	Interest rate
t	Time

1. Introduction

The flow balance in fluid distribution networks transfers fluid based on the needs of network consumers. Transmission networks consist of loops and nodes, where loops are the paths connecting the source to the consumer, and nodes are the consumers of the network. The geometric characteristics of the transmission network are formed based on the needs of the consumer and the power of the producer. Drops in the piping circuit cause non-compliance of the consumer's needs with the production capacity of the source. The set of losses caused by the roughness of the pipe surface, the change in the cross-sectional area of the flow passage, the change in the angle and direction of the flow, as well as the losses caused by the presence of valves in the piping route cause inconsistency in the flow distribution. Direct and reverse piping network models are two examples of the most common closed circuit piping methods, but these networks have many losses that cause the lack of proper distribution of current in the network. On the one hand, this issue causes energy loss; on the other hand, it imposes many startup costs on the system.

This article examines the common methods of piping closed circuits and identifies their weak points. In the first step, the amount of waste caused by improper flow distribution is examined. In the next step, the effect of flow balance at consumer points will be investigated. Energy transmission networks are known by two names: direct return (traditional) and reverse return (modern). But these two transmission networks have their advantages and disadvantages and they do not perform the current transmission process properly. The first goal of this research is to investigate the disadvantages of the above methods.

The numerical method used in the existing research is numerical calculations based on the Newton-Raphson method. The intended network for performing numerical calculations is based on the pattern of closed piping circuits of energy supply systems. The issue of flow balance has been analyzed based on numerical calculations, and its effect on reducing the consumption of working fluid in the hydronic network will be evaluated. The considered numerical solution will examine two traditional and modern models and compare their results with the optimal model. After comparing the above circuits with each other and also with the optimal circuit, the amount of energy consumption, production of carbon dioxide gas, and the cost of setting up and operation will be evaluated.

To check the system performance cost, a period of 50 years is defined, and calculations are made based on exchange rate changes in this period. One of the results of the present research will be to reduce the consumption of the working fluid and also to reduce the capacity of the pumping system in the closed-circuit network, which in turn reduces the cost of setting up and also reduces the energy consumption for the flow distribution. In other words, in this article, the effect of flow balance on the reduction of water consumption and also energy consumption caused by water transfer will be investigated over 50 years. The result of this article can be used in industrial and construction fluid transmission networks so the use of the technique presented in this article will reduce the implementation cost and also reduce water consumption. An energy supply system consists of three different and intertwined parts: production, distribution, and control of energy consumption. Energy supply systems can be national, regional, local, or centralized, and can include electricity, fossil fuel supply, hot or cold water supply, hot or cold air, or steam. The purpose of this article is to examine the supply of hot or cold water and steam or hot oil in industrial and residential heating and cooling networks. The energy supply circuits in which water is responsible for energy transfer as a fluid are called hydronic networks. Energy supply in hydronic networks has three phases: production, distribution, and control of energy consumption. In the first phase, fossil fuels or renewable energy can be used to heat or cool the working fluid. In the energy distribution phase, the operating fluid is sent to consumers. This transmission or distribution of the stream has a non-linear nature, which makes distribution a challenge. In the third phase, the control of energy consumption occurs, which depends on various parameters on the side of the energy consumption and is a complex matter according to the consumer's use. [1]–[9]

The desired part of this research is the second phase of energy supply, which is the distribution part of the energy carrier flow. The energy-carrying flow consists of a working fluid with a certain temperature, and its purpose is to transfer energy to the consumer to provide optimal heating or to transfer energy from the consumer to provide optimal cooling. The desired agent fluid in this research is water, which is the same in the field of industrial and residential heating and cooling. As mentioned, the working fluid will be hotter or colder during the energy production stage. In other words, the temperature of the operating fluid is increased or decreased with the intention that at the point of contact with the consumer, if heating is required, heat transfer from the operating fluid to the consumer occurs, and if cooling is required, heat transfer from the consumer to the operating fluid occurs. This requires proper distribution of current in the energy supply system at a regional, local, or central scale. [3]–[12]

Flow distribution means transferring the working fluid to the consumer according to the consumer's needs. Transferring more than the consumer's needs will cause more heat to be transferred (to or from) the consumer, and as a result, the consumer's desired temperature will not be created. This is due to improper flow rate with the desired heat level of the consumer. The desired flow rate at the consumption point should be calculated and provided exactly according to its use. Consider a set of consumers, each of which is located at a different distance from the source of energy supply. In addition to the different distances from the energy supply source, the amount of heat transfer is also different in each of them, resulting in a different and sometimes variable desired flow rate of heating or cooling for each consumer. Energy distribution in the mentioned system occurs due to current transfer in the heating and cooling closed circuit network. Water, as the working fluid, flows through the head increase by using the pumping system in the closed-circuit network. Therefore, the heated (or cooled) water in the energy supply source should be directed to the consumers. [13], [14]

As mentioned, the distance of consumers from the source of energy supply and their desired flow rate are different from each other. The main challenge in the energy distribution phase starts from this point, which is how to provide the optimal flow rate for each consumer in different parts of the network through a fixed or even variable cycle pumping system. The desired network can be regional, local, or centralized, and hydronic closed-circuit networks can be implemented in two ways: direct piping or reverse piping. In direct piping, the working fluid flow first enters the nearest consumer and finally exits from the farthest consumer and is transferred to the energy supply source. In reverse piping, the flow of the operating fluid enters the nearest consumer at first, but the outflow of the fluid towards the energy supply sources starts again from the nearest consumer. [15], [16]

According to the research conducted by Hegberg, the pumping system is determined and selected according to the required flow rate and head drop in the heating system [17]. The required flow rate is determined by the thermal load for process or space heating and is transferred according to the size of the piping network. Each piping network will create a certain pressure drop according to its size (pipe diameter), as a result of which a certain flow rate will pass through it and will not exceed a certain value. Therefore, the property of the pipe and the flow through it, the pumping system cannot send more than a certain amount of water. The old pumping systems had a fixed rotation speed and water flow rate, but in recent years, variable-speed pumps have been produced that can change the water flow rate [18]. By changing the consumption of electrical energy, this technology changes the pump speed and thus changes the water flow rate[19] . White and his colleagues in their studies show that energy-carrying fluid transmission technologies include serial piping, tee connections, direct return piping network, and reverse return piping network. The serial piping method is the simplest and cheapest piping model, but it has imprecise control over the flow rate and temperature of the system. Tee fittings have made it easier to control the temperature while being more expensive, but their main problem is energy loss. Two-pipe networks are the common piping system in our country, but their problem is that they are expensive to set up. At the same time, they have the possibility of little control over the flow rate and temperature of the network [11]. Existing research showed that the design of the water transmission network is based on the absence of air, and this system is most efficient in the absence of air. During installation and management, air molecules enter the water, and problems such as reducing the amount of contact of hot water with metal surfaces and reducing the fluid heat transfer rate, creating noise due to air movement, causing cavitation phenomenon, corrosion, and decay of the metal surface due to the presence of oxygen and air in hot water [20]. Recent research regarding the creation of energy-free buildings has led to the presentation of new methods that have investigated the role of geographical location and its effect on the amount of energy required by the building [21], [22]. Compliance with these climatic points will provide energy according to the consumer's needs. Valves play a very important role in the water supply network by controlling flow and pressure, releasing air, and preventing fluid return. The ability of different valves to control energy consumption, such as the air valve, can increase the efficiency of the piping system. By properly understanding the effect of different valves on energy loss in a system, the cost of the network operation period can be reduced, and suitable solutions can be suggested [23]. The influence of flow and return temperature in heating water transmission networks was carried out by Lavenberg and his colleagues so that at first, they investigated the flow temperature of 90°C and the return temperature of 70°C and then the flow temperature of 60°C and the return temperature of 40°C [24], [25]. Baoping et al. researched the installation of thermostatic valves on the piping network and finally provided a way to reduce the return temperature [26]. Lind and colleagues researched the economic ways of hot water transmission networks [27]. By examining non-residential buildings as well as their conditions for energy supply, Lambard and colleagues extracted computational code and modeling to provide the required temperature of the space. The result of their research is providing a model for supplying energy to non-residential buildings[28]. Hu and his colleagues investigated a number of air conditioning projects, investigated the amount of energy required according to the comfort temperature of the residential space, and analyzed a number of factors affecting this issue. The result of their research is providing methods for better regulation of comfort temperature [29]. Mohammad Royapoor and his colleagues have conducted studies on air conditioning automation and according to their findings, hydronic circuit control is rarely carried out in a precise and scientific way [30]. Tardi et al., relying on the science of energy economics, have done research on providing comfort temperature in cold places and the result of their research is providing a model based on sustainable and economical energy supply [31]. Navaji et al. developed a model for using solar energy for heating or cooling using environmental temperature conditions. The findings of these researchers indicate the effects of environmental temperature conditions on the amount of heat transfer by domestic consumers [32]. Mohammad Hassan and colleagues have reviewed studies on the activities carried out in the field of modeling, simulation, performance, control, and integration of radiation cooling methods. Their most important achievement is the control strategy in the hydronic circuit pumping system [33]. Cabeza and colleagues believe that in order to reduce climate change, the energy stored in building materials should be reduced. This can be achieved through the use of materials with less energy storage, increasing energy efficiency, and replacing fossil fuels with renewable energy sources [34]. Mathews and colleagues have tried to provide a new method for simulating the energy supply and comfort temperature of the building by relying on computational fluid dynamics methods. Their research has led to the production of methods to calculate and provide comfortable temperatures using natural ventilation [35].

As mentioned, many kinds of research have been conducted on providing comfortable temperatures for residential buildings and also providing optimal temperature for buildings with special uses such as hospitals or industries with special chemical processes such as pharmaceuticals, in all of which the aim of providing the optimal temperature is a process. The study of all the above articles as well as all the research carried out regarding the accurate provision of the optimal temperature of the processes shows that all the research until today focused on heat production systems (boilers), hot fluid transfer systems (pumps, and networks) piping and valves, control systems (thermostats). However, providing the desired temperature is still a complicated and difficult matter and has created many problems in the field of energy consumption. Due to accurate engineering calculations in energy production, transmission, and control, we still see the lack of accurate provision of the desired temperature, and the reason for this is that the calculations were made only on separate phases of energy production, transmission, and control. In other words, in order to provide the desired temperature, three stages of calculation and design are performed separately, including the energy production phase, the energy transfer phase, and the energy control phase. However, in the conditions of exploitation, these three issues work continuously and closely and affect each other [23], [25], [36].

As stated, what challenges energy issues in engineering processes more than anything else in today's modern world is the energy economy. Comprehensive research on the cost of the life cycle of the internal temperature regulation system of the building has been done in such a way that the conducted modeling is based on the air entering the building, the air leaving the building, heat recovery, airflow control, and the heating and cooling supply system. As presented in the LCC model, the initial cost of purchasing and setting up heating and refrigeration systems, the costs including the energy required for operation, and periodic maintenance costs have also been considered. In the above modeling, the cost of land is also considered as the initial cost of the system, and finally, according to the mentioned cases, the LCC model was presented to determine the appropriate heating and cooling system for the building. The research conducted using the LCC technique has investigated and evaluated the energy supply process in the design phase of a building and performed modeling based on the shape of the building, building materials, building structure, room arrangement, and building heating and cooling systems. In order to choose the optimal cooling system of a building based on the LCC method and by using the data obtained from energy over the past 25 years, it can be found that the cost of running the building during 25 years of operation in proportion to the cost of energy and the cost of maintenance can be between 40 up to 75% of the cost of its implementation and operation [37]–[39]. The current article evaluates energy distribution networks from two technical and economic perspectives in a 50-year time span, and its innovation is to provide a solution and a model for proper and cost-effective energy distribution in transmission networks.

The work presented in the paper focuses on the life cycle cost of a balanced hydronic system. The novelty of this research lies in its contribution to understanding the cost implications of utilizing potable water as a hydronic medium in multi-unit residential buildings. By analyzing the performance and cost aspects, the paper aims to provide insights into potential cost savings during installation and operation.

The study explores the potential for reducing specific life cycle costs by optimizing energy use in space heating and cooling. By minimizing delivered energy and life cycle costs, the research aims to identify strategies for achieving cost-effective retrofitting in office buildings. This approach offers a novel perspective on minimizing life cycle costs while considering energy efficiency.

The paper also addresses the importance of hydronic balancing in achieving a balanced flow distribution within the system. This aspect is crucial for ensuring that all zones receive proportionate flow under design conditions, which can lead to improved energy efficiency and cost-effectiveness.

The work presented in the paper contributes to the broader field of life cycle cost analysis and optimization. It aligns with the growing interest in evaluating the environmental and economic sustainability of various heating and cooling systems. By combining simulation and optimization techniques, the research aims to minimize the life cycle cost of a detached house.

In summary, the work presented in the paper offers a novel perspective on the life cycle cost of a balanced hydronic system. It explores the cost implications of utilizing potable water as a hydronic medium, investigates strategies for minimizing life cycle costs in retrofitting scenarios, and emphasizes the importance of hydronic balancing. The research contributes to the broader understanding of optimizing energy use and achieving cost-effective solutions in the field of hydronic systems.

2. Methodology

In order to carry out the current research, the research system and space must be defined first. After defining the system and its surrounding environment, the system performance modeling should be checked. This modeling is divided into two parts, the first part is physical modeling and the second part is economic modeling. In the next step, the initial conditions and the boundary conditions of the problem will be determined, and the problem-solving will begin with computational coding. The results obtained from the physical and economic modeling will be verified by comparison with the results of the pilot project.

According to the mentioned cases, the investigated system is an energy transmission network, the fluid of which is water, and its purpose is to transfer energy from the energy source to the consumers who are connected to the source in parallel. The two energy transmission networks discussed in this research are the network with direct return and the network with the reverse return. Modeling of energy transfer in the mentioned networks will be done based on the Hardy-Cross method, and the numerical solution will be done using the Newton-Raphson calculation method. The initial and boundary conditions of the problem are determined according to the flow rate, system temperature, and ambient temperature, and the goal of the numerical solution is to reach the desired temperature in the consumer. Economic modeling is done based on the life cycle cost method and basic information including startup cost, energy, maintenance, and carbon dioxide emissions will be considered in proportion to the system volume. After extracting the results of physical and economic modeling, the obtained results will be examined with a real project.

2.1. Modeling

The piping system that transfers the working fluid from the energy production source to consumers has a unique system curve. This curve displays the flow rate and head required to transfer the working fluid to consumers at different points in the network. Recent research by the Air Conditioning Association of America indicates that heating and cooling systems have a functional range that includes a set of flow rates and heads of the hydronic network, which also includes the system curve [40], [41]. To calculate the relationship between pressure-drop and flow rate in a piping network, the Darcy-Weissbach equation can be used.

The Darcy-Weissbach equation

$$h_{l(pipe)} = kQ^n, n = 2,\ k = \frac{8.f.L}{g.\pi^2.D^5} \tag{1}$$

The given text describes the relationship between pressure drop and flow rate in a circular pipe. The pressure drop in a pipe has a direct relationship with the length of the pipe and its surface roughness, and it has an inverse relationship with the fifth power of the pipe diameter. The Darcy-Weissbach equation can be used to calculate the relationship between pressure drop and flow rate in a circular pipe. However, to calculate the relationship between pressure drop and flow rate in a closed-circuit network, the principle of similarity is used, assuming that the conditions of the piping network are constant. The pressure drop in a pipe has a direct relationship with the flow rate and an inverse relationship with the fifth power of the pipe diameter. The Darcy-Weissbach equation can be used to calculate the pressure drop per unit length of the pipe.

$$\frac{h_{l(pipe)2}}{h_{l(pipe)1}} = \frac{Q_2^n}{Q_1^n} \tag{2}$$

Therefore, the above relationship can be converted into the following form, which shows the behavior of flow and pressure in a closed-circuit network:

$$H_a = H_2 + \left(\frac{Q_a}{Q_1}\right)^{1.9}.(H_1 - H_2) \tag{3}$$

The relationship between flow rate and pressure drop in the hydronic network is non-linear, which makes it difficult to determine the required load for other consumers when the load changes in one of the consumers. A change in the flow rate of one consumer will cause a change in the flow rate of other consumers, which can disrupt the hydronic network. Additionally, the above relationship is derived based on the physical and geometrical parameters of the hydronic circuit. Any change in the geometric and physical parameters of the hydronic network can cause a change in the above relationship. For example, a change in the cross-section of the pipe due to sedimentation can change the speed and flow rate in a section of the pipe, which can change the above relationship. Similarly, a change in the degree of opening or closing of a valve in a consumer can also change the parameters of the above relationship. Therefore, the above relationship is not only non-linear but also highly dependent on the physical parameters of the flow.

2.2. Pumping system and head losses

The pumping system in a closed hydronic circuit is responsible for transferring the working fluid from the energy source to the consumers while minimizing flow losses and returning the working fluid to the energy source. However, issues such as deposits in the piping circuit changes in the opening rate of consumers' valves, or changes in the type and load required by consumers can cause changes in flow losses. Therefore, the pumping system must have the ability to provide new working pressures and be designed to perform at a lower level than its designed value in conditions where the pressure drop is lower than the designed value, known as partial load conditions. Partial load conditions occur when the heating or cooling system operates at a point other than the design point due to changes in process requirements or environmental temperature changes, resulting in the withdrawal of energy consumers from the circuit. In such a situation, the flow rate of the pumping system should be reduced without changing the system. However, changing the flow rate in pumping systems poses many problems. The purpose of this research is to determine and adjust the flow required by consumers without changing the pumping system [18], [42], [43].

In full load conditions of the hydronic system, the pumping system will work correctly if there is no change in the piping route due to sedimentation or local closing of the consumers. However, in partial load mode, the pumping of the working fluid may not be suitable for the needs of consumers. According to the principles governing the movement of fluids, the transmission of the working fluid in the hydronic network always occurs in the path that has the lowest drop, and then the working fluid will move to the paths with a higher drop. This issue is the main challenge in the transmission of the working fluid in the hydronic network, which is referred to as energy distribution or energy balance. The exact distribution of current in the energy transmission network is called balance or current balance. The modeling of the stated problem will be done to solve this issue.

2.3. Governing Equations

Equations governing the flow in hydronic closed-circuit networks can be solved using the Hardy-Cross method. This method ensures that the sum of input flows to any point in the network is equal to the output flows, and the total pressure drop in a loop will be zero. Modeling of energy transfer in the mentioned networks will be conducted using the Hardy-Cross method, which requires an initial estimate of flow in each pipe to satisfy the continuity equation for each junction node. The numerical solution will be achieved using the Newton-Raphson calculation method. The problem's initial and boundary conditions are determined based on factors such as flow rate, system temperature, and ambient temperature. The objective of the numerical solution is to attain the desired temperature in the consumer.

The Hardy-Cross method is an iterative approach commonly employed for determining flow in pipe network systems where the input and output flows are known. This method allows for the analysis of flow distribution in the network and ensures that the continuity equation is satisfied at each junction node. It is widely used in the analysis of pipe networks and has been applied to various fields, including water supply networks and gas distribution networks. The following relations are extracted for a case of a loop of a closed-circuit network:

The sum of the head loss in each pipe loop is zero.

The head loss in each pipe is proportional to the flow rate in that pipe.

The head loss in each pipe is proportional to the square of the flow rate in that pipe.

The head loss in each pipe is proportional to the length of that pipe.

The head loss in each pipe is inversely proportional to the fifth power of the diameter of that pipe.

The Hardy-Cross method is an iterative method for determining the flow in pipe network systems where the inputs and outputs are known, but the flow inside is unknown. This method requires an initial estimate of flow in each pipe so that the continuity equation for the junction nodes is maintained.

Continuity Equation

$$\mathrm{Q_a} = \mathrm{Q_b} + \mathrm{Q_c} \tag{4}$$

Energy Equation

$$\Sigma h_l = 0 \rightarrow \Sigma k\left(Q + \Delta Q\right)^n = 0 \tag{5}$$

The above relation will be expanded as follows, which should be used for numerical solution.

$$\Sigma k Q_a^n + \Sigma nk\left(\Delta Q\right) Q_a^{n-1} + \Sigma \frac{n-1}{2} nk\left(\Delta Q\right)^2 Q_a^{n-2} + \ldots = 0 \tag{6}$$

To calculate the required flow of each consumer in the hydronic network, the above relationship can be solved. Two hydronic networks with a number of consumers are considered to investigate the above relationship, in which energy distribution occurs with the two methods of direct return piping network and reverse return. The purpose of this section is to analyze the required flow rate in each section of the hydronic network and compare the flow rates of each section in the direct return and reverse return piping system.

The Hardy-Cross method can be used to solve the equations governing the flow in hydronic closed-circuit networks. This method ensures that the sum of input flows to any point in the network is equal to the output flows, and the total pressure drop in a loop will be zero. The hydraulic equilibrium condition is achieved when the flow rate is found by plotting the head loss curve of the hydronic circuit. The flow rate in each pipe of the network can be calculated using the Hardy Cross method, which is commonly used to analyze pipe networks [8], [9], [12], [44], [45].

3. Numerical solution of flow governing equations

3.1. Flow modeling in distribution network with direct return

The hydronic network with direct return and 10 loops and 11 consumers has a deviation of approximately 27% from the standard in partial load conditions and about 10% in full load conditions when the entire system is in use. This means that the system is always 10-27% less than the standard value of the current supplier for consumers. The below figure shows this.

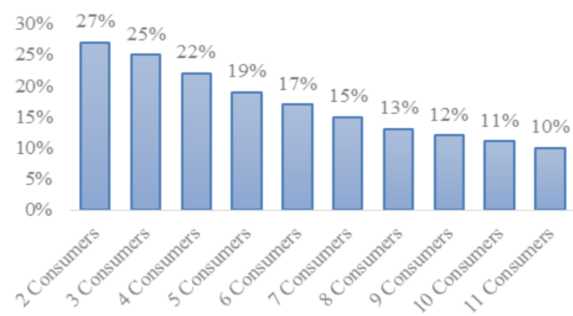

Fig. 1. Deviation from the standard of transmitted flow in the network with direct return

3.2. Flow modeling in distribution network with reversal return

The hydronic network with reverse return and 10 loops and 11 consumers has a deviation of almost 45% from the standard in part-load conditions and around 8% in full-load conditions when the entire system is in use. This means that the system is always 8-45% less than the standard value of the current supplier for consumers. The results obtained from the transmission network with reverse return indicate that the deviation from the standard is higher compared to the direct return network. The physics necessary for dividing the overall system flow into equal streams that pass through several identical components is simple. When designing a piping system, it is important to ensure that the flow is divided equally. This can be achieved by making sure that the flow resistance of each piping path from a common source point to a common return point is the same. This simple physics concept can be used to divide the overall system flow into equal streams that pass through several identical components.

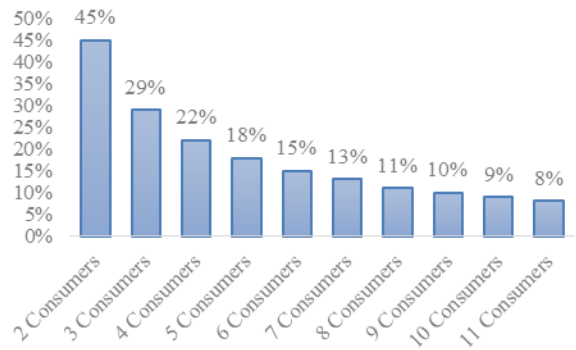

Fig. 2. Deviation from the standard of transmitted flow in the network with reverse feedback

The above graphs show a high deviation from the desired flow in both types of transmission networks. The optimal transmission network should adjust and supply the working fluid flow according to the consumer's needs. However, all energy transmission lines, whether at the household level or at the level of the country's transmission network, are designed and implemented based on pipes with a constant surface and valves that are always open, which results in the inefficiency of the direct and reverse transmission network. Although the flow distribution is better in the reverse return piping network compared to the direct return piping network, the flow rate will still not match the needs of the consumers due to the rigid and geometrically unchanged closed hydronic circuit. The diameter of the flow passage in the pipes is always affected by phenomena such as sedimentation, making flow rate changes over time uncontrollable. Moreover, if the energy supply and transfer of the energy-carrying fluid are controlled only based on the pump speed and the change in the pumping rate, we will face the challenge of flow control in places far away from the pump. Therefore, the need to control flow in branches or flow consumers is very important. The flow rate of each consumer should be controlled to reduce the input flow rate to the consumers in points close to the pumping system (energy source) and transfer the excess flow rate to the distant consumers. This can balance and stabilize the flow in the energy distribution network without spending money and using the same piping network and pumping system. The only solution to this problem is the use of flow control valves that have the ability to adjust the flow rate for different consumers.

3.2.1. Hydronic Balancing Method

Despite the use of the reverse piping network, energy distribution remains problematic. The hydronic piping network includes pipes, fittings, valves, welded and ribbed pipes, and fittings will remain unchanged during the operation period of the system. Therefore, it will not be possible to change pipes and fittings for flow control during the operation period, and the only available equipment during the operation period of an energy supply system is its valves. By changing the cross-sectional area of the flow rate entering the consumers, a local pressure drop can be created in the hydronic circuit, and the flow rate entering the consumer can be adjusted. The data obtained from the numerical analysis of the governing equation of the energy distribution network show that the nonlinear behavior of the system curve in hydronic circuits causes too much operating fluid to enter the nearby consumers in such a way that in the points close to the energy source, we will always face the challenge of oversupplying energy needs and as a result, energy waste. On the contrary, in remote areas, we always face the challenge of not supplying the required energy. To control the flow of each consumer, a local pressure drop can be created in the piping network by limiting the cross-sectional area of the incoming flow to each consumer. This can help to balance and stabilize the flow in the energy distribution network without changing the piping network and pumping system. Balancing valves should still be installed in each branch of a reverse return system to fine-tune the flow rates to their calculated design load values[26], [42], [46], [47].

3.3. Economic modeling: Life cycle cost of heating and cooling system

To calculate the life cycle cost, the following relationship should be used: [15]

$$LCC = \sum_{t=0}^{N} \frac{C_t}{(1+d)^t} \tag{7}$$

The total costs of the system are:

Initial cost

As described previously, the initial cost includes the following:

a. Design, supply, transportation, installation and operation of equipment

b. Construction of workshop, shed and land preparation

c. Investment cost or the initial amount of capital required

3.3.1. Maintenance cost during operation period

An energy supply system should operate optimally for a 50-year operation period after the start-up phase. Periodic maintenance costs include repairs, replacement of worn parts, service and inspection of critical and productive parts, and supply of spare parts. These costs should be calculated using the present value method of a recurring fixed amount and considered for the exploitation period. The net costs in an energy supply system are considered to be 10% of the investment cost of the equipment and will be calculated annually through the present value (PV) relationship for a fixed recurring amount.

3.3.2. Efficiency of heating and cooling systems

The efficiency of the heating and cooling systems considered in this research are as follows:

a. The efficiency of thermal systems is around 85% at the beginning of the operation period.

b. The efficiency of refrigeration systems has a COP (efficiency) coefficient of 3.

3.4. The cost of producing pollution

The cost of greenhouse gas emissions can be calculated by using an average of $42.29 per ton of carbon dioxide emissions caused by the combustion of natural gas or the use of electricity. However, this figure varies in European and American countries and depends on the economic conditions of the country. To calculate the cost of greenhouse gas emissions, the mentioned number will be used for each ton of carbon dioxide emissions caused by the combustion of natural gas or the use of electricity in this research. [48]–[51].

According to the latest studies regarding the amount of carbon dioxide gas production in exchange for the combustion of one cubic meter of natural gas, the production amount of this greenhouse gas will be equal to [52]:

$$1.96\,\frac{kg\ CO_2}{m^3\ CNG}$$

According to the latest studies on the amount of carbon dioxide gas produced in exchange for the combustion of one cubic meter of diesel fuel, the amount of this greenhouse gas production will be equal to[52]:

$$2677.3\,\frac{kg\ CO_2}{m^3\ diesel}$$

According to the latest studies regarding the amount of carbon dioxide gas production to supply 1-kilowatt hour of electrical energy, the production amount of this greenhouse gas will be equal to[52]:

$$7.09\times10^{-1}\,\frac{kg\ CO_2}{kWh}$$

3.5. The results of the life cycle cost modeling of the transmission network

The optimal transmission network is based on the direct return transmission network, but with flow control valves in all branches to solve the problems of the direct transmission network. The volume of piping, water required, energy, and greenhouse gas production in the optimal transmission network is 30% less than the transmission network with a reverse return. In other words, an artificial pressure drop or flow control valve is required for each consumer. Adding a flow control valve for each consumer will increase the investment, start-up, and maintenance costs. However, during the operation period, the lifetime cost of the optimal transmission network will be much lower than the reverse and even direct transmission network, despite the higher investment, start-up, and repair costs. The life cycle cost of the energy transmission network in a 5-story building or a complex with 5 parallel consumers shows that the cost of the pipe network with a reverse return is 19% more than the pipe with a direct return, and the cost of the piping network with direct return in the same 50-year period is 19% more than the balanced network. The cost of the network with reverse return will be 42% higher than the balanced network. The cost of the pipeline network with reverse return in a complex with 20 consumers in the 50-year operating period is 47% more than the network with direct return, while the network with direct return is 5% more than the balanced network. The difference in the cost of the network with a reverse return compared to the balanced network in this group will be 55%. The life cycle cost of a set with 30 parallel consumers in a 50-year operating period shows that the cost of the reverse network is 51% more than the direct network and 56% more than the balanced network. The difference between the direct network and the balanced network is only 3%. [44], [45], [53]

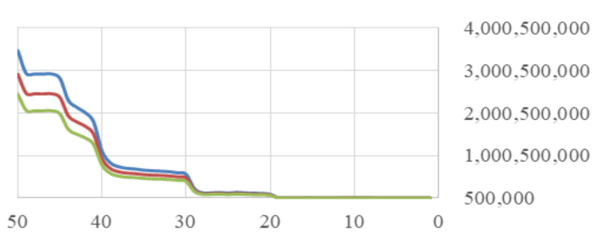

Fig. 3. Life cycle cost of the energy network related to a 5-story building(Green: Optimized, Red: Direct Return, Blue: Reverse Return)

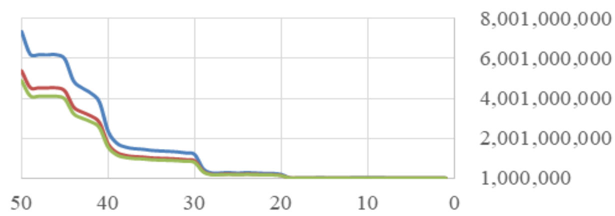

Fig. 4. Life cycle cost of the energy network related to a 10-story building(Green: Optimized, Red: Direct Return, Blue: Reverse Return)

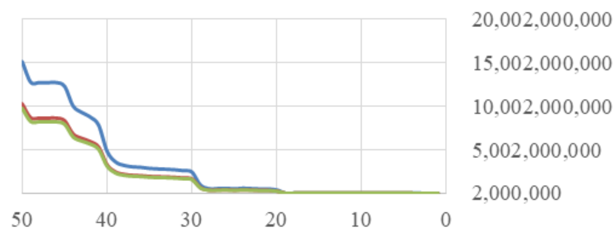

Fig. 5. Energy network life cycle cost related to a 20-story building (Green: Optimized, Red: Direct Return, Blue: Reverse Return)

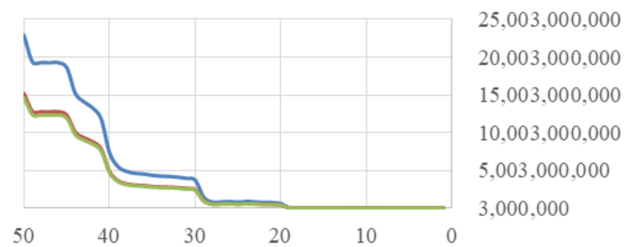

Fig. 6. Energy network life cycle cost related to a 30-story building (Green: Optimized, Red: Direct Return, Blue: Reverse Return)

3.6. Investigating the effect of density on the life cycle cost

The impact of consumer concentration on the energy transmission network and its costs is analyzed in the following graphs. Investigating the effect of congestion on the energy transmission network will determine the optimal point in choosing the transmission network type. Fig. 7 compares the effect of density on the life cycle cost of two sets with 10 consumers. The first set has 10 parallel consumers, and the second set has two networks with 5 parallel consumers. Figure No. 7 examines these two sets when their energy transmission network is in three types: reverse, direct, and optimal. The obtained data show the cost ratio of two networks with 5 consumers compared to one network with 10 consumers. In the 50-year period, the cost of the reverse network of two sets with 5 consumers is 6% less than one set with 10 consumers, while this issue is the opposite in the direct network, and its cost is 8% more. However, the optimal network will not have a difference in cost because all consumers receive energy according to their needs.

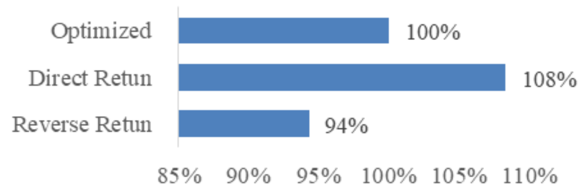

Fig. 7. Comparison of the effect of congestion in the life cycle cost of two networks with 5 consumers compared to one network with 10 consumers in a period of 50 years.

Figure 8 illustrates the impact of congestion on the life cycle cost of networks with different numbers of consumers. The figure compares the cost of energy transmission in a set of four networks with 5 consumers to a network with 20 consumers. According to the figure, in the long term, the cost of energy transmission in the reverse network for a set including four networks with 5 consumers is 8% less than the integrated set with 20 consumers. However, in the direct network, it is the opposite and about 13% more. The optimal network still shows the same cost despite the congestion. This suggests that congestion has a significant impact on the cost of energy transmission, and it is important to consider the number of consumers in a network when designing and implementing energy transmission systems.

Figure 9 compares the cost of a set of 2 networks with 10 units to a set of 20 units. According to figure number 9, the cost of the reverse network is 3% less, and the cost of the direct network is 5% more. The comparison of graphs 8 and 9 shows that the cost of energy transmission is affected by the type of network used and the level of congestion. Specifically, if the direct network is used, the cost of the dense network is lower than the discrete network, and if the reverse network is used, the discrete network will cost less than the dense network.

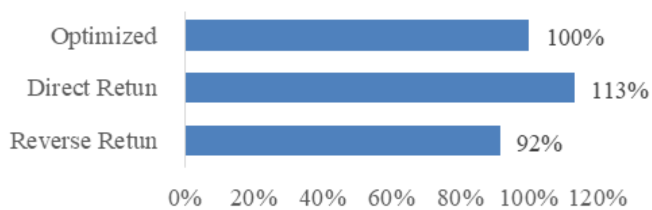

Fig. 8. Comparison of the effect of congestion in the life cycle cost of four networks with 5 consumers compared to one network with 20 consumers in a period of 50 years

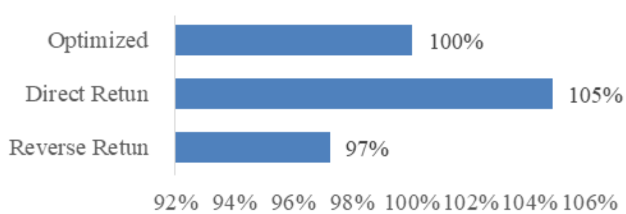

Fig. 9. Comparison of the effect of congestion in the life cycle cost of two networks with 10 consumers compared to one network with 20 consumers in a period of 50 years

Figure 10 compares a set including six networks with 5 consumers with a set with 30 consumers. In this case, the reverse network will cost 9% less, and the direct network will cost 15% more. Figure 11 shows the reduction of the cost difference in the long term in case of higher density. Figure 11 compares a set including three networks with 10 consumers with a set including 30 consumers. In this case, the reverse network will cost 4% less, and the direct network will cost 7% more. Comparing graphs 10 and 11 shows that dense sets will cost less if the direct network is used, and if the discrete set is considered, inverse networks will have better efficiency. Investigating the effect of congestion on the energy transmission network will determine the optimal point in choosing the transmission network type.

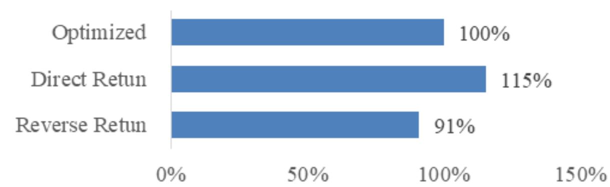

Fig. 10. Comparison of the effect of congestion in the life cycle cost of six networks with 5 consumers compared to one network with 30 consumers in a period of 50 years

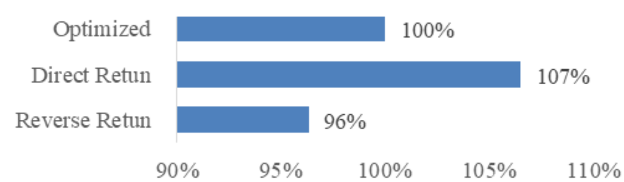

Fig. 11. Comparison of the effect of congestion in the life cycle cost of three networks with 10 consumers compared to one network with 30 consumers in a period of 50 years

3.7. A case study of the life cycle cost of the energy transmission network iv a residential building

The intended residential building has three residential floors with an area of 120 square meters, which is heated by a central heating engine fueled by natural gas. The consumption of natural gas is measured by a volumetric meter. The engine house is equipped with a hot water boiler and a gas burner to heat the working fluid, which is hardened water. The heated working fluid is transferred to the residential spaces through the energy transmission network inside the building, which is of reverse return piping type made of black steel pipe. The energy transmission network is not balanced, and the process of transferring the working fluid is done by electric pumps. The domestic radiators transfer the energy of the working fluid to the secondary fluid, room air. The lifespan of the building during the test period was 16 years. The purpose of this research is to examine the life cycle cost of the energy transmission network of the building using the conventional method and to analyze it after the renovation of the building and the flow balance of the energy transmission network. The connections of the piping network are of welding type, and the connections of its valves are of threaded type. The research aims to determine the optimal point in choosing the transmission network type by investigating the effect of congestion on the energy transmission network [1], [3], [4], [7], [54].

3.7.1. Modeling of the existing energy transmission network

According to the calculations and investigations carried out during the operation period of the desired energy supply system, its life cycle cost function is as follows: [8], [12], [44], [45], [53]

The following relationship shows the cost of setting up and maintaining an energy supply system with a reverse return network according to the needs of the target building.

$$f_{old}(t) = 5852.1(t^6) - 168936(t^5) - 10^6(t^4) + 8*10^7(t^3) - 7*10^8(t^2) + 2*10^9(t) + 2*10^9 \quad \textbf{(8)}$$

Optimum energy transmiddion network modeling

If the energy supply system uses the optimized direct return network and the balance of energy distribution is used in a standard way, the life cycle cost function of the system works as follows:

$$f_{opt}(t) = 4473.7(t^6) - 129144(t^5) - 10^6(t^4) + 6*10^7(t^3) - 5*10^8(t^2) + 1*10^9(t) + 2*10^9 \quad \textbf{(9)}$$

The life cycle cost of the energy supply system can be reduced by 33% by changing the energy transmission network from the reverse return network to the optimized direct return network in the studied building. This means that during the 16 years of the system operation period, the life cycle cost would be reduced by 33%.

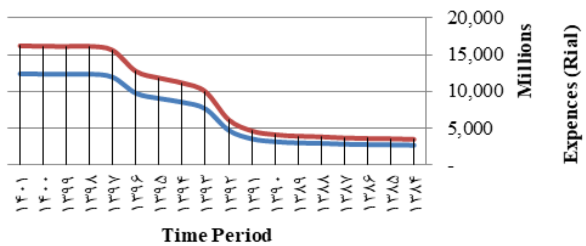

Fig. 12. Energy transmission network life cycle cost (Red Line: Traditional System, Blue Line: Optimized System)

3.8. Life cycle cost of optimal transmission network

The optimal transmission network is based on the direct return transmission network, but with flow control valves in all branches to solve the problems of the direct transmission network. The volume of piping, water required, energy, and greenhouse gas production in the optimal transmission network is 30% less than the transmission network with reverse return, and it has flow control valves in all branches. In other words, an artificial pressure drop or a flow control valve is required for each consumer. Adding a flow control valve for each consumer will increase the investment, start-up, and maintenance costs. However, according to the above graphs, which compare the lifetime cycle cost of the optimal transmission network with the direct and reverse transmission network, it can be seen that despite the higher investment, start-up, and repair costs, in the long term, the lifetime cost of the optimal transmission network will be less than the reverse transport network [9], [55]–[57].

3.9. Comparision of case study results

After the numerical calculations and theoretical modeling of the life cycle cost, a case study of an energy supply system was conducted to evaluate the modeling. A 3-story residential building with 3 active consumers was selected, and the energy transmission network was evaluated over 7 years to check energy consumption. The data were registered and called consecutively through the gas meter. The energy transmission network in the complex was evaluated before and after renovation. In the first year of operation, the desired energy transmission network was used without flow balance, and the amount of natural gas consumption in the coldest period of the year was about 4400 cubic meters. After the flow balance and balance of the energy transmission network in the last two years, the consumption of natural gas in the coldest period of 1400 was about 2200 cubic meters, and in 1401, this value reached 1900 cubic meters. The results of natural gas consumption clearly show that balancing the energy transmission network has reduced natural gas consumption by about 50%.

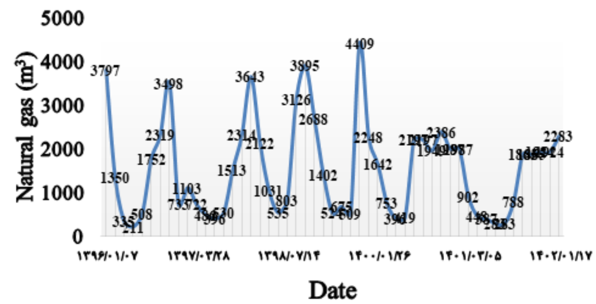

Fig. 13. Natural gas consumption (cubic meters)

4. Result analysis

The case study conducted on the energy distribution network of the target building shows a 50% reduction in natural gas consumption. This reduction in energy consumption, maintenance costs, and pollution production proves that energy supply systems with reverse distribution networks can be easily optimized. The modeled life cycle cost shows a 33% reduction in energy supply costs if the distribution network is optimized. The comparison of the above two cases shows that both theoretically and practically, the reduction of energy consumption and emission of polluting gases is an achievement for the energy distribution network.

5. Discussion

The article titled "The Effect of Flow Balance on the Reduction of Life Cycle Cost in Hydronic Networks" analyzes two models of the most common energy transmission networks in industrial and residential processes. The results show that energy transmission networks do not have a uniform and regular flow in the branches and sub-branches of the main circuit because they are a function of a non-linear process. This issue causes uncontrollable energy transfer in the branch leading to the consumer, which brings heavy costs to the environment and the transmission and energy supply network in the long run. The design of the energy transmission system should provide optimal energy more than the needs of the consumers to avoid excess energy production, which causes an increase in the production of greenhouse gases and depreciation and operating costs. The type of energy transmission network shows a different result compared to the density of consumers. The costs of the reverse network in discrete sets are lower than those of dense sets, while in the direct network, the costs of dense sets are lower than those of discrete sets. The study of the effect of congestion shows that balancing the energy transmission network is the best and cheapest action in the long term.

The use of the reverse return network inherently has energy consumption in excess of the consumer's needs, which results in additional production of carbon dioxide around 30-40% of the standard. The use of the direct network along with the artificial pressure drop can reduce the production of carbon dioxide to the minimum possible amount. The article concludes that the use of conventional networks is harmful, and new designs, as well as existing networks, must be balanced to reduce energy consumption and pollution production.

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