Water Loss Diagnosis of Heating Network Based on Thermal Inverse Problem

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Abstract. The fact that residential customers steal heating hot water can result in serious loss of heating pipe network and bring serious security risks to the heating pipe network as well as boilers, which leads to relatively high heating cost. In this study, we put forward the method of using the infrared thermal image of building exterior wall to analyze the interior room temperature and finally determine the malicious water users. Divide the building by vertical unit then the problem is simplified to two-dimensional steady-state heat transfer modeling. According to the outside-wall temperature, the convection heat transfer coefficient and the actual temperature in the room are chosen as the inversion goal, and the actual temperature of each room in the whole building is calculated. Then combined with the input heat of the heat transfer station, the abnormal heat room can be determined. Lastly, considering the relationship between the indoor temperature changes of neighbors can accurately identify malicious water loss.

Introduction

In northern China, more than 85% residents use central heating system with water as working medium in winter. Some families steal the hot water in pipes for bathing, washing, mopping the floor, washing cars and so on. This has led to a loss of water in the heat supply network and caused many problems. Due to loss much water, the imbalance of the second heating network system result in abnormal heating. The water loss brings hidden danger to the safe operation of the boiler in first heating network system, causes the system to be paralyzed and may lead to serious accidents. It also causes waste of fuel, water and electricity, and costs more money. In addition, water loss led to deterioration of other households heating, and led to new troubles between the heating companies and community residents [1, 2]. Therefore, researching a novel water-loss identification technology become particularly urgent and important.

Innovative Idea

In normal heating areas, the change of building temperature is a continuous change in time and space. In the process of temperature change, external heat sources, including hot water losing, air conditioning and electric heater heating, etc., will lead to changes in the temperature of the room, the change is different from the normal state. Although the room temperature can’t be directly obtained, infrared radiation can be used to sense the temperature distribution outside the building.

Room temperature is not only related to the temperature inside the room, but also with the size of the room, location, external weather, housing structure and many other factors [3]. Taking into these factors, the multi-objective heat transfer inverse function is established and the real temperature of each room is calculated by inversion calculation. On this basis, the temperature difference and temperature difference trend of each room are calculated. Comparing the heat input change of thermal substation, the room temperature anomaly is screened. Water loss will lead to an imbalance of hot water system in this room. Checking the change of the temperature of the surrounding room and the temperature variation trend of the room and the nearby room in the historical database, to eliminate the interference factors such as opening the air conditioning and the electric heater, etc., the accurate
judgment of the water-loss residents is made. At the same time, it can also find the heat dissipation of
the residents and the heat loss of the pipeline, which is beneficial to improve the heating scheme.

**Heat Transfer Model**

Considering the calculation efficiency and the stability of the solution, the three-dimensional heat
transfer can be simplified into two dimensional heat conduction problems. It consists of two
directions, the height of the building and the thickness of the window. For a multi-cell building, many
times calculations are performed using same way. The partitioning of the computing unit is shown in
Figure. 1.

![Calculation unit](image1.png)

**Figure 1. Calculation unit.**

According to the actual heat transfer condition, the heat conduction between the unit and the unit is
neglected, and the wall structure of each floor is assumed to be identical. The above calculation unit
can be simplified as a steady two-dimensional heat conduction model with constant physical property
and without internal heat source, as shown in Figure. 2.

![Two-dimensional steady thermal conduction model](image2.png)

**Figure 2. Two-dimensional steady thermal conduction model.**

The thermal boundary conditions are

\[
\begin{align*}
C_1 : & T = f(y), x = 0 \quad \text{(Get by infrared thermal imaging)} \\
C_2 : & \frac{\partial T}{\partial y} = C, y = 0 \quad \text{(Fixing heat flow on the ground)} \\
C_3 : & \lambda \frac{\partial T}{\partial x} = h(T - T_\infty), x = x_i \\
C_4 : & \lambda \frac{\partial T}{\partial y} = h(T - T_\infty), y = y_s
\end{align*}
\]

where: \( T_\infty \) is the internal temperature of the room, \( \lambda \) is the thermal conductivity of the wall or the
window, \( h \) is the convective heat transfer coefficient of the wall or the window.

Thermal control equation:

\[
\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0 \tag{1}
\]

The whole calculation region is separated into \((M-1)\times(N-1)\) meshes by finite difference method. A
positive problem can be obtained by the boundary conditions, the temperature at each node is \( T_{ij} = T(x_i, y_j) \). The temperature displayed on the infrared thermal image is the temperature at \( x = 0 \). Where, \( x_i = x_s(i-1)/(M-1), y_j = y_s(j-1)/(N-1), i=1, 2, ..., M; j=1, 2, ..., N. \)

**Inversion for Room Temperature**

**Inversion Objective Function**

The temperature inside the room is more difficult to measure than the outdoor temperature. While the
exterior wall temperature can be determined by infrared thermography. In this research, the interior
temperature is obtained by the exterior wall temperature inversion. The objective of the inversion is to
find the appropriate indoor temperature distribution, which make the following objective function reach to the minimum:

\[ J(R) = \sum_{i=1}^{M} [T_i^c - T_i^m]^2 \]  

(2)

In formula 2, \( T_i^c \) is the calculation temperature of the exterior wall measurement point, and the positive problem of heat transfer is obtained by the guess of indoor temperature. The inverse problem is equivalent to determining the temperature vector \( R \) when the objective function \( J(R) \) reaches its minimum.

**Inversion Method**

Conjugate Gradient Method (CGM) is a mature gradient optimization algorithm [4], which has high accuracy and stability for the inverse heat transfer problem of multi variable and multiple thermal boundary conditions. In this research, the method is used as an inversion tool.

CGM constructs a set of conjugate directions to search for the minimum value of the objective function to be optimized. A series of indoor temperature distribution functions of different floors \( T_{i,j} (i=1,2,\ldots,M) \) was solved by CGM. The iterative method is:

\[ T_{i,j}^{n+1} = T_{i,j}^n + \beta^n s_i^n \]  

(3)

where, \( \beta^n \) is the search step, and \( s_i^n \) is the conjugate search direction.

\[ s_i^n = -g_i^n + \varphi_n s_i^{n-1} \]  

(4)

where

\[ g_i^n = \frac{\partial J}{\partial T_{i,1}} = 2 \sum_{k=1}^{G} [T_k^c - T_k^m] \frac{\partial T_k^c}{\partial T_{i,1}} \]  

(5)

The conjugate coefficient \( \varphi_n \) is calculated by the following formula:

\[ \varphi_n = \frac{\sum_{i=1}^{M} (g_i^n)^2}{\sum_{i=1}^{M} (g_i^{n-1})^2} \]  

(6)

The search step size \( \beta^n \) is obtained by optimizing the objective function \( J(T_{i,j}^n + \beta^n s_i^n) \).

\[ \beta^n = \frac{\sum_{k=1}^{G} [(T_k^\text{cal} - T_k^\text{meas})(\sum_{i=1}^{M} \frac{\partial T_k^\text{cal}}{\partial T_{i,1}} s_i^n)]}{\sum_{k=1}^{G} (\sum_{i=1}^{M} \frac{\partial T_k^\text{cal}}{\partial T_{i,1}} s_i^n)^2} \]  

(7)

where, \( \frac{\partial T_k^\text{cal}}{\partial T_{i,1}} \) can be determined by central difference approximation.

**Inversion Solution Programming**

CGM needs computer programming. The process is as follows.

I. Given a small positive as \( \varepsilon \), select the indoor temperature distribution of guess value \( T_{i,j} (i=1,2,\ldots,M) \). The temperature at the measuring point \( K \) is calculated by formula (1), and is marked as \( T_k^c (k=1,2,\ldots,G) \).
II. To determine whether the following conditions are met.

\[ J = \sum_{k=1}^{G} (T_k^e - T_k^m)^2 < \epsilon \]  

If satisfied, stop iterating, or else continue.

III. The conjugate coefficients \( \varphi_n \), gradients \( g_i^n \), search directions \( s_i^n \) and search steps \( \beta^n \) are calculated respectively by formula (4) - (7);

IV. To make \( n=n+1 \) update the inversion parameters according to formula (4) and return to step II.

Case Analysis

FLIR ThermaCAM P30 infrared camera is used to collect the thermal image of residential buildings, as shown in Figure. 3. P30 is an uncooled focal plane infrared imager with an infrared resolution of 320x240 and four temperature measurement sections. In this experiment, the temperature range of -40~50 degree Celsius is adopted, and the measuring accuracy is 0.1 degree Celsius.

According to the investigation, the wall thickness of the residential building is 0.315m. The average thermal resistance is 0.95(m²·K) /W [5]. Under the meteorological conditions, the convective heat transfer coefficient of outdoor 23.3W/(m²·K) is taken as reference[6]. In Figure. 3, the building consists of 17 layers. An outer wall temperature is obtained from each floor of a unit from the infrared thermography, as shown in Figure. 4. Based on this temperature, the room temperature of the unit is retrieved.

As shown Figure. 4, due to the different structures and heat transfer conditions, the difference in temperature is displayed. At the same time, the rationality of using CGM method to retrieve indoor temperature is also proved.

Water-loss Room Discrimination

Water loss in the building will cause hydraulic changes in the building. In severe cases, vertical hydraulic disturbances may occur, which result in changes in temperature within each room of the vertical plane. A hydraulic model of the building unit is created, as shown in Figure. 5.

This unit is made up of 5 floors. Each floor is 3m high and the ground floor is 1m from the ground. A ball valve is installed on the third floor to drain water, which simulate the user to discharge the water secretly. The model is a typical heating system. The water net is powered by a circular centrifugal pump with constant pressure water supply device, the pressure is 0.1MPa (gauge). The heating area of room is 120m² in the simulation. Consider the non-energy-saving old buildings, heat intensity is 33W/m² [7]. Adjust the opening of the valve from 0-70%, the heat dissipation of the room radiator shown in Figure. 6 shows.

As shown Figure. 6, when the drain valve opens from the 0-70%, the heat dissipated on each floor varies markedly. The amount of heat dissipated in the rooms below the 3th floor decrease and the room temperature drops. Higher rooms heat dissipation increase and the temperature increase, too.
Especially the heat dissipation of the water-loss room increase more. This heat dissipation is only the heat released by the radiator normally. In the water-loss room, if hot water is used for mopping, bathing, washing clothes, etc., the room temperature will rise even greater. The amount of heat dissipation will result in room temperature changes of 1~5 DEG C. This change can be easily captured by an infrared camera with a sensitivity of 0.1 DEG C.

In addition, it is found that when the drain valve opening is greater than 59%, there is a reverse flow in the simulation, part of the backwater from 4th and 5th floor flow out directly from the drain valve. This phenomenon can lead to serious vertical hydraulic disturbances on all floors and may cause other problems. It will be studied in future.

![Heat dissipation](image1.png)

![Valve opening vs heat release](image2.png)

**Figure 5. Heating system model.**  
**Figure 6. Floor heat dissipation when 3th floor is out of water.**

### Conclusion

In this paper, the surface temperature of building was measured by wide angle infrared thermal image. The actual temperature of the room in the building is calculated by inverse calculation using the infrared images. To screen out abnormal temperature rooms is the basis on next step to determine.

The water-loss influence on neighbor heating is also analyzed by simulation. The heating changes will eventually reflect the temperature changes in the surrounding room. Combined with the thermal emerge input curve of the heating station and the historical temperature change of the building, the water-loss room is determined accurately. It lays a solid theoretical foundation for developing and designing a water-loss room identifying system based on infrared images.

The infrared imaging technique is effective for finding the water-loss rooms in the heating area. It provides a new idea for centralized heat supply management of town residential district. It provides a new way for central heating management.

### References


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