# INVESTIGATION OF TEMPERATURE VARIATION OF COLD WATER IN THE PIPING OF A WATER CHILLER SYSTEM

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**ABSTRACT**

Water from the chiller of a central air conditioning system is distributed to FCU or AHU heat exchangers through a piping system. Along the flow direction, the water constantly absorbs heat from the surrounding air by convection and conduction through the pipe material, increasing its temperature as it moves. To determine the temperature variation of water along the flow direction, which serves as a basis for calculating heat loss through the pipes and determining the thickness of the insulation layer to meet technical requirements and investment costs, this paper has developed a mathematical equation to determine the temperature variation of water along the flow direction based on establishing the heat balance equation of water in the pipes. The research results not only optimise the design calculation process for central air conditioning systems but also provide a methodology for calculating temperature variations in other systems, such as hot water supply systems.

***Keywords:*** *Heat transfer in chilled water pipes, chilled water temperature variation, water temperature in water chiller systems, heat loss in chilled water pipes.*

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## 1. INTRODUCTION

A central water-based air conditioning system uses chilled water from a water chiller (WC) and transports the water through a piping system to FCU (fan coil unit) or AHU (air handling unit) heat exchangers. These units regulate temperature and humidity in the room. Figure 1 shows the chilled water circulation diagram for this system.

Due to its technical characteristics not being limited by the length of the chilled water pipe or the height difference between the water chiller and the heat exchangers, as well as the ability to handle air temperature and humidity compared to air conditioning systems using refrigerants that directly handle temperature and humidity, the water-based central air conditioning system is very suitable for buildings with large heat loads or buildings where other air conditioning systems cannot meet the height difference between the condenser and evaporator, such as the central air conditioning system VRV (Variable Refrigerant Volume) outdoor and indoor of 90m [7] or a maximum of 110m for the Multi V system [12]; especially the strict requirements for air temperature and humidity in the room.

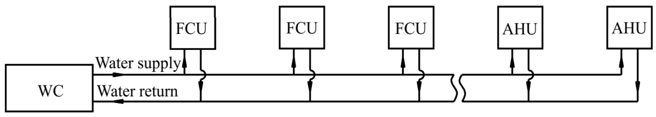


Figure 1. Chilled water circulation diagram of a water chiller system

Depending on the purpose of use, the water chillers of central air conditioning systems usually produce chilled water with a temperature in the range of 5°C to 9°C [14, 16]. Because chilled water has a lower temperature than the ambient air temperature, there is always heat loss when water moves in the pipes. To minimise heat loss to the environment and to avoid condensation on the surface of the pipes, it is necessary to have an insulating layer wrapped around the pipes from the water chiller to the FCU or AHU heat exchangers.

In fact, when designing central air conditioning systems, it is often assumed that the temperature of the circulating water in the pipes remains constant and equals the temperature of the water from the water production unit. However, the water temperature increases along the flow direction due to heat loss to the surrounding environment. This makes it difficult to calculate heat loss through chilled water pipes and determine the optimal thickness of the insulation layer. In this study, we determine the temperature variation of chilled water flowing through the pipes of a central air conditioning system by establishing an energy balance equation for the water in the system. From this, we determine the heat loss through the pipes and the insulation layer to ensure technical requirements are met, thereby saving energy and investment costs for the system.

## 2. PROBLEM SOLVING

### 2.1. Mathematical equations to determine the change in temperature of cold water

As mentioned above, because the temperature of the cold water in the pipeline system is lower than the ambient air temperature, there is always a certain amount of heat entering the pipeline, increasing the temperature of the cold water from the water chiller to the heat exchangers, causing energy loss. According to heat transfer theory, the process of heat transfer from the outside air environment to the moving water environment in the pipe is by convection, radiation between the pipe surface and the environment, and conduction through the layers of material. Here, the ambient air temperature around the outer surface of the pipe is low, the usage range is usually between $20^0C \div 28^0C$ [2, 4]; the temperature of the circulating water in the system is also low, depending on the purpose of use, the temperature of the water supplied to the heat exchangers is in the range of $5^0C \div 9^0C$ or $10^0C \div 14^0C$ for the water returning to the chiller [5]. Because the ambient temperature around the pipe surface is low, the heat exchanged by radiation is very small compared to the heat transfer methods by conduction and convection and can be ignored in calculations without encountering significant errors [1, 9].

From the above analysis, heat is transferred from the outside air to the inside of the pipe by convective heat dissipation between the pipe surface and the environment, and by conduction through the layers of material, causing the enthalpy of water to increase in the direction of flow. To establish the energy balance equation for water, the following assumptions must be accepted:

- Because the insulation layer and the cold-water pipe are in direct contact with each other, the thermal resistance at the contact point between the two layers of material can be ignored without encountering significant errors [9].

- Since the diameter of the water pipe is much smaller than its length, the temperature gradient of the water perpendicular to the flow can be ignored without significant error [3].

- The thermophysical parameters of the pipe and the insulation material remain constant.

Based on the assumptions, consider any pipe section along the flow direction with length dl as shown in Figure 2.

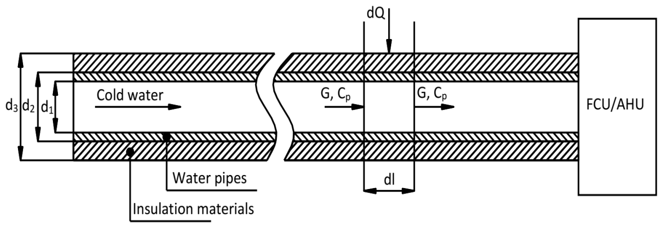


Figure 2. Model for calculating the variation of cold-water temperature

The heat balance equation for the water in the pipe section under consideration is as follows:

$$G.di = K_l.(t_{f1} - t).dl \quad (1)$$

In there:

G - cold water mass flow, kg/s.

$t_{f1}$ - air temperature around the pipe, $^0C$.

t - cold water temperature at the calculation location, $^0C$.

i - enthalpy of water, J/kg.

$K_l$ - heat transfer coefficient of the pipe, W/m.K.

It is observed that the thickness of the steel layer of the cold water pipe and the thickness of the insulation layer are much smaller than the pipe length, so the heat transfer process through the material layers is considered a one-way heat conduction process without encountering significant errors in calculation [3, 9]. Then the heat transfer coefficient of the pipe is determined according to the formula [3, 9]:

$$K_l = \frac{1}{\frac{1}{\pi.d_1.\alpha_T} + \frac{1}{2.\pi.\lambda_1}.\ln\frac{d_2}{d_1} + \frac{1}{2.\pi.\lambda_2}.\ln\frac{d_3}{d_2} + \frac{1}{\pi.d_3.\alpha_N}} \quad (W/m.K)$$

Here:

$d_1$, $d_2$ - inner diameter and outer diameter of the water pipe, m

$d_3$ - outer diameter of the insulation layer, m

$\lambda_1$, $\lambda_2$ - thermal conductivity coefficients of the water pipe and the insulation material, W/m.K

$\alpha_T$ - convective heat transfer coefficient between the inner surface of the pipe and the water, $W/m^2.K$

$\alpha_N$ - convective heat transfer coefficient between the outer surface of the insulation layer and the air, $W/m^2.K$

As mentioned above, the range of chilled water usage of central air conditioning systems is usually 5°C ÷ 9°C for water supplied from the water chiller or 10°C ÷ 14°C for water returned to the water chiller [5], so the water does not change phase during movement in the pipe. Therefore, the heat balance equation (1) can be written as:

$$G.C_p.dt = K_l.(t_{f1} - t).dl \tag{2}$$

Here, $C_p$ is the specific heat capacity of water at constant pressure, J/kg.K.

The water from the chiller has a temperature. $t'_n$ [$^0$C], and water at any position along the direction of movement to the heat exchangers has a temperature $t''_n$ [$^0$C]. From equation (2), the transformation we get:

$$\int_{t'_n}^{t''_n} \frac{dt}{(t_{f1}-t)} = \int_0^L \frac{K_l}{G.C_p}.dl \tag{3}$$

Here: L is the length of the cold water pipe, m

Therefore, the water temperature at a distance L from the starting point is:

$$t''_n = t_{f1} - (t_{f1} - t'_n).e^{-\frac{K_l}{G.C_p}.L} \tag{4}$$

Equation (4) allows for determining the water temperature at any point along the flow direction. This serves as a basis for calculating heat loss through the pipe and determining the insulation layer that meets technical requirements to save energy and investment costs.

### 2.2. Method for determining the heat transfer coefficient

In a hydraulic central air conditioning system, because water moves in the pipes and air moves around the outer surface of the pipes, convective heat transfer always occurs between the inner surface of the pipes and water and the outer surface of the pipes and air [1, 3, 9]. To determine the temperature variation of water, it is necessary to determine these convective heat transfer coefficients. Many studies have been conducted to calculate the convective heat transfer coefficients when water moves in the pipes or when air moves around the outer surface of the pipes, and these research results can be found in [8, 9, 11, 13]. The basic problem when determining the convective heat transfer coefficient to ensure accuracy is to choose a standard equation that is suitable for the actual boundary conditions of the problem. Fand, R. M [8] developed a standard equation that allows the determination of the convective heat transfer coefficient between the outer surface of the pipe and the surrounding environment within the Reynolds number range from $10^{-1}$ to $10^5$. This standard equation was used by Eckert E. R. G., and R. M. Drake [6] to calculate the heat exchange coefficient of the flow across the outer surface of the pipe and yielded results with an error not exceeding 5%. Based on the actual boundary conditions of the research object, which is a cold-water pipe placed indoors with air moving around the pipe, Fand, R. M's standard equation [8] will be selected to calculate the convective heat transfer coefficient between the outer surface of the pipe and the air. The standard equation has the following form:

$$Nu_f = \left(0{,}35 + 0{,}56.Re_f^{0{,}52}\right).Pr_f^{0{,}3}$$

for $Re_f = 10^{-1} \div 10^5$ (5)

In the equation above, the defined temperature is the average temperature of the air surrounding the tube, and the defined size is the outer diameter of the tube.

In the case of water moving in a pipe, many studies have developed standard equations to determine the convective heat transfer coefficient between the inner surface of the pipe and the liquid. Typical examples include the Karman-Boelter-Martinelli standard equation when $Pr > 0.7$ or the Sleicher and Rouse equation when $Pr << 1$, mentioned in [15]. However, using the Karman-Boelter-Martinelli equation is very complicated as it requires determining many physical quantities in the similarity standard, while using the Sleicher and Rouse equation is limited by the Prandtl value, which is greater than 7 in the temperature range from 5°C to 14°C [1]. The Dittus-Boelter standard equation [10] is used by many authors to calculate the convective heat transfer coefficient when water moves in a pipe. The equation has the following form:

$$Nu_f = 0{,}0243.Re_f^{0{,}8}.Pr_f^{0{,}4}$$

for $0{,}7 < Pr < 160$ and $Re > 10^4$ (6)

Given the actual boundary conditions in this study, the standard equation of Dittus-Boelter [10] was chosen by us to determine the convective heat transfer coefficient between water and the inner surface of the pipe. To determine the convective heat transfer coefficient using the standard equation (6), we need to know the temperature of the water moving in the pipe. However, the variation of water temperature in the pipe is an unknown that needs to be determined in this study. Nevertheless, we have calculated the convective heat transfer coefficient using equation (6) when the water temperature varies by 2°C and found that the calculation error does not exceed 2%. This calculation result confirms that using the average convective heat transfer coefficient will not have significant errors in this study.

## 3. RESULTS AND DISCUSSION

Table 1. Calculation parameters for cold-water temperature variation

| $N_0$ | Parameter | Symbol | Value | Unit |
|---|---|---|---|---|
| 1 | Inner diameter of the cold-water pipe | $d_1$ | 200 | mm |
| 2 | Pipe thickness | $\delta_1$ | 5 | mm |
| 3 | Thermal conductivity coefficient of cold-water pipes | $\lambda_1$ | 25 | W/m.K |
| 4 | Thickness of the insulation layer | $\delta_2$ | 40 | mm |
| 5 | The thermal conductivity coefficient of the insulation material layer | $\lambda_2$ | 0.032 | W/m.K |
| 6 | Ambient air temperature around the pipe | $t_{f1}$ | 25 | $^0C$ |
| 7 | Cold-water temperature at the initial calculation point. | $t'_n$ | 5 | $^0C$ |
| 8 | The speed of water movement in the pipe | $\omega_n$ | 2.41 | m/s |
| 9 | The speed of air movement | $\omega_k$ | 0.20 | m/s |

From the above research results, using standard equation (5) and standard equation (6) with the calculated parameters in Table 1, the convective heat transfer coefficient between water and the inner surface of the pipe is determined to be 4516.48W/m$^2$K; the convective heat transfer coefficient between air and the outer surface of the pipe was 3.32W/m$^2$K. This calculation result is consistent with the studies on convective heat transfer between the surface and the surrounding environment mentioned in [6, 8, 11, 13]. The calculated heat transfer coefficient value is an important parameter to determine the temperature variation of water with flow. From the research results shown in equation (4), the temperature variation of water with flow direction was determined. The calculation results are shown in Table 2 and on the graphs in Figure 3 and Figure 4.

From the above research results, the temperature distribution of water in the pipe was calculated with the calculation parameters shown in Table 1. In which the calculation parameters of the cold-water pipe were taken

Table 2. Calculation results of water temperature distribution and pipe outer surface temperature along the flow

| $d_1$, m | $d_2$, m | $d_3$, m | $a_1$, W/m$^2$K | $a_2$, W/m$^2$K | G, kg/s | L, m | $t_{f1}$,$^0C$ | $t_n'$,$^0C$ | $t_n''$,$^0C$ | Q, W | $t_{w1}$,$^0C$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 5 | 25 | 5.00 | 5.01 | 47.914 | 21.83 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 10 | 25 | 5.01 | 5.02 | 47.888 | 21.83 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 15 | 25 | 5.02 | 5.03 | 47.849 | 21.83 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 20 | 25 | 5.03 | 5.05 | 47.798 | 21.84 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 25 | 25 | 5.05 | 5.08 | 47.734 | 21.84 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 30 | 25 | 5.08 | 5.11 | 47.657 | 21.85 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 35 | 25 | 5.11 | 5.15 | 47.568 | 21.85 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 40 | 25 | 5.15 | 5.19 | 47.465 | 21.86 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 45 | 25 | 5.19 | 5.24 | 47.351 | 21.87 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 50 | 25 | 5.24 | 5.29 | 47.224 | 21.87 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 55 | 25 | 5.29 | 5.35 | 47.084 | 21.88 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 60 | 25 | 5.35 | 5.41 | 46.933 | 21.89 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 65 | 25 | 5.41 | 5.48 | 46.769 | 21.90 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 70 | 25 | 5.48 | 5.56 | 46.594 | 21.92 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 75 | 25 | 5.56 | 5.63 | 46.406 | 21.93 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 80 | 25 | 5.63 | 5.72 | 46.207 | 21.94 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 85 | 25 | 5.72 | 5.81 | 45.997 | 21.96 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 90 | 25 | 5.81 | 5.90 | 45.775 | 21.97 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 95 | 25 | 5.90 | 6.00 | 45.542 | 21.99 |
| 0.2 | 0.21 | 0.29 | 3.32 | 4516.48 | 75.6 | 100 | 25 | 6.00 | 6.10 | 45.298 | 22.00 |

from the technical specifications of ASTM A53 galvanised steel pipe. Water temperature parameters were taken from the cold-water production machine [14, 16]; water flow velocity was taken from [5]; temperature and air flow velocity around the pipe were determined based on indoor comfort conditions [2, 4].

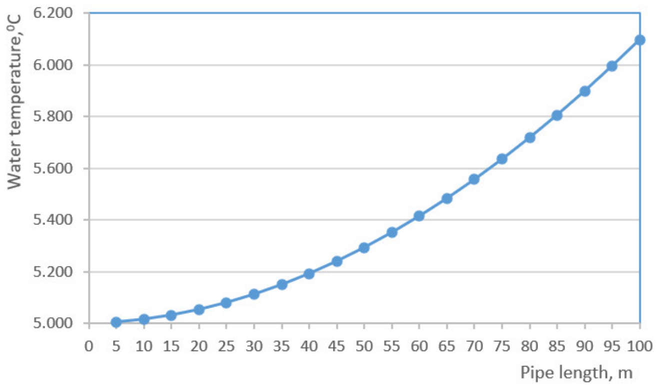


Figure 3. Water temperature distribution pattern along the flow direction

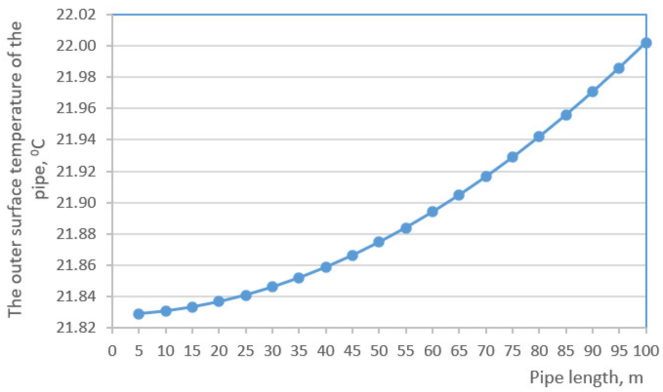


Figure 4. Temperature distribution pattern at the outer surface of the pipe along the flow direction

From Table 2 and Figure 3, Figure 4 shows that the water temperature inside the pipe and the outer surface temperature of the pipe increase exponentially along the flow direction. The increase in water temperature along the flow direction is due to heat transfer from the air environment through the pipe material layers into the inside, and along with the increase in water temperature along the flow direction is a gradual increase in the outer surface temperature of the pipe, resulting from convective heat transfer between the pipe surface and the surrounding air environment. The calculated results of the variation of water temperature and the outer surface temperature of the pipe are consistent with the heat transfer law mentioned in [3] and [9]. The calculation results allow determining the distribution of heat loss along the pipe length, thereby accurately determining the total amount of heat loss through the pipe.

With the calculated parameters in Table 1 and a pipe length of 100m, the total heat loss through the pipe is 939.1W. In practice, this heat loss is often ignored when calculating the heat load for central air conditioning systems. However, the calculation results show that the heat loss through the pipes is significant and should be considered when calculating the heat load for the system. The insulation layer around the pipes not only plays a role in minimising heat loss from the chilled water but also plays a crucial role in ensuring that condensation does not occur on the pipe surface. If the pipe surface temperature is lower than the dew point temperature of the surrounding air, condensation will occur on the pipe surface. With the parameters in Table 1, the research results determined the minimum temperature at the pipe surface to be 21.83°C. This temperature value is greater than the dew point temperature of the indoor air environment, which is 20.2°C, corresponding to comfortable conditions with a temperature of 25°C and relative humidity of 65% [2]. At that time, condensation does not occur on the pipe surface, ensuring technical requirements are met. From this, the appropriate thickness of the insulation layer can be determined to both ensure technical requirements and minimise investment costs. Accordingly, with the calculation parameters as in Table 1, but reducing the thickness of the insulation material layer to 35mm, 30mm, and 25mm.

Table 3. Calculation results of heat loss and outer surface temperature of the pipe when changing the thickness of the insulation layer

| **Pipe length** | **$d_2$ = 35mm** | | **$d_2$ = 30mm** | | **$d_2$ = 25mm** | |
|---|---|---|---|---|---|---|
| L, m | Q, W | $t_{w1}$, $^0$C | Q, W | $t_{w1}$, $^0$C | Q, W | $t_{w1}$, $^0$C |
| 5 | 52.510 | 21.46 | 58.303 | 21.00 | 65.833 | 20.39 |
| 10 | 52.480 | 21.46 | 58.265 | 21.00 | 65.785 | 20.39 |
| 15 | 52.433 | 21.47 | 58.208 | 21.00 | 65.712 | 20.40 |
| 20 | 52.372 | 21.47 | 58.132 | 21.01 | 65.615 | 20.41 |
| 25 | 52.294 | 21.48 | 58.037 | 21.01 | 65.494 | 20.41 |
| 30 | 52.202 | 21.48 | 57.923 | 21.02 | 65.349 | 20.42 |
| 35 | 52.095 | 21.49 | 57.791 | 21.03 | 65.180 | 20.44 |
| 40 | 51.972 | 21.50 | 57.640 | 21.04 | 64.988 | 20.45 |
| 45 | 51.835 | 21.51 | 57.470 | 21.05 | 64.773 | 20.47 |
| 50 | 51.682 | 21.52 | 57.283 | 21.07 | 64.534 | 20.48 |
| 55 | 51.515 | 21.53 | 57.077 | 21.08 | 64.272 | 20.50 |
| 60 | 51.333 | 21.54 | 56.854 | 21.10 | 63.988 | 20.52 |
| 65 | 51.137 | 21.55 | 56.613 | 21.11 | 63.682 | 20.54 |
| 70 | 50.927 | 21.57 | 56.354 | 21.13 | 63.354 | 20.56 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 75 | 50.703 | 21.58 | 56.078 | 21.15 | 63.004 | 20.59 |
| 80 | 50.464 | 21.60 | 55.786 | 21.17 | 62.633 | 20.61 |
| 85 | 50.212 | 21.62 | 55.477 | 21.19 | 62.241 | 20.64 |
| 90 | 49.947 | 21.63 | 55.151 | 21.21 | 61.829 | 20.67 |
| 95 | 49.668 | 21.65 | 54.810 | 21.24 | 61.397 | 20.70 |
| 100 | 49.377 | 21.67 | 54.453 | 21.26 | 60.945 | 20.73 |

From the calculation results in Table 3, it can be seen that when reducing the insulation thickness from 40mm to 25mm and with a pipe length of 100m, the total heat loss increases from 939.1W to 1280.6W; at the same time, the calculation results also show that the minimum temperature at the outer surface of the pipe with a thickness of 25mm is 20.39$^0$C, this temperature value is approximately equal to the dew point temperature of the surrounding air environment of the pipe under comfortable conditions with a temperature of 25$^0$C and relative humidity of 65% [2] as mentioned above. From this, it can be confirmed that, with the calculated parameters in Table 1 and with the ambient air temperature around the pipe at 25°C and relative humidity at 65%, a thickness of 25mm of insulation material is the minimum thickness required to insulate the pipe to ensure technical requirements are met and no condensation forms on the surface.

The accuracy of the calculation results needs to be verified experimentally or evaluated through previously published research results. In this study, the computational model was built based on a detailed analysis of the heat transfer mechanism between cold water moving in the pipe and the surrounding environment, as well as establishing assumptions that realistically assess the boundary conditions and the calculation results consistent with the heat transfer law mentioned in [3, 9]. It can be affirmed that the research results are reliable and can be practically applied to the design of central air conditioning systems.

## 4. CONCLUSION

- Based on an analysis of the heat transfer mechanism in the cold-water pipes of a water chiller system, by establishing a heat balance equation for water, the temperature distribution pattern of the water along its direction of movement has been determined. This is a new scientific result that can be applied to calculate heat loss through pipes for central water chiller air conditioning systems and determine the appropriate insulation material to ensure both technical requirements of minimising losses and preventing condensation on the surface are met, while also reducing investment costs.

- The research results not only contribute to optimising the design calculation process of central air conditioning systems but also provide a methodology for calculating temperature variations for other systems, such as hot water supply systems.

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