Dynamic Cooling Load Calculation of Heat Transfer through the Envelope for Cold Storage

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Abstract. The dynamic heat transfer method is adopted, the mathematical model of reaction coefficient method is established and programmed, and a very practical dynamic load engineering algorithm for the wall of cold storage is obtained, which will provide reliable basic data for the continuous automatic regulation and energy saving control of the whole system dynamic real-time load of the cold storage. The calculated heat flow is much smaller than the current heat flow calculated according to the code insulation, and the maximum heat flow is much smaller than the current heat flow calculated according to the code insulation. The method presented in this paper can also be applied to the design and check of the thickness of the insulation layer and the analysis of the wall condensation in the wall system of the cold storage.

1. Introduction
According to the data released by the national development and reform commission, China is the world’s largest producer, consumer, and exporter of refrigeration. The cooling power consumption account for more than 15\% of the total power consumption in China. The energy consumption of cold storage is mainly in the refrigeration system, which is 60\% to 70\% of total energy consumption. The energy consumption of cold storage is closely related to the selection of the outdoor environment parameters, the calculation of heat transfer cooling load through the building envelope and the heat insulation design for the building envelope. At present in China, the main focus of the energy saving of cold storage is refrigeration efficiency and the heat insulation design for the building envelope based on steady state heat transfer, and that the calculation of the cooling load through the building envelope is also based on steady state heat transfer, there is almost no controlled refrigeration on hourly energy consumption based on hourly energy consumption calculation and analysis. With gradual strictness of the national macro energy conservation policy, a job that must be done that the continuous automatic regulation and energy saving control of cold storage based on dynamic real-time load of the whole system, which will put forward new practical requirements for the selection of outdoor environment temperature calculation parameters, the calculation of cold storage envelope load and the insulation design of cold storage envelope.

2. Analysis of the present situation and the problems to be solved
At present, there are obvious defects in the selection of outdoor meteorological parameters applied to the calculation of cold storage enclosure cooling load in the code for design of cold storage. Compared with the outdoor calculated temperature, the average value of the annual average temperature of the hottest day and night, outdoor calculated dry bulb temperature of air conditioning in summer and the weighted average temperature of the hottest month and the extreme maximum temperature over the
years which have been successively used in the past history, although the daily average temperature of air conditioning in summer used at present reduces part of the calculated cooling load and appropriately reduces the investment, its defects are also very obvious. First, all the above outdoor meteorological parameters do not reflect that the outdoor air temperature exists as an external disturbance boundary condition with periodic fluctuation factors, second, the above outdoor meteorological parameters only reflect the outdoor air temperature, not the influence of solar radiation, outdoor cold storage is greatly affected by solar radiation, which is also the external disturbance boundary condition with periodic change factors.

At present, the method of wall insulation design and cooling load calculation in cold storage code is still steady-state heat conduction, without considering the change of cooling load. Generally, the total thermal resistance value of the enclosure is determined by the upper limit value of the heat flow of the enclosure, and then the thickness of the insulation layer is determined. Based on the steady-state heat transfer, the heat transfer of the enclosure in the calculation result is steady-state heat transfer. The heat flow and total heat transfer coefficient reflect the effect of heat preservation under steady state heat transfer, but not under unsteady state heat transfer.

Most of the traditional civil cold storage enclosures are heavy thermal inertia structures with thermal inertia index $D > 6$, and their attenuation is very large, generally hundreds to thousands of times; the delay time is very long, generally more than 19 hours, some more than one fluctuation period (24 hours), indicating that part of the heat of the enclosure after the delay in the daytime will be transferred to the outdoor with the decrease of outdoor temperature at night. The attenuation of medium thermal inertia structure (4 < $d < 6$) is also large, and the delay time is more than 10 hours. However, the traditional cold storage enclosure structure built in accordance with the civil engineering mode in the past in China has high energy consumption, low temperature, low strength and short service life, which is not suitable for the operation mode of modern cold chain. With the development of building industrialization and the popularization of building component factory production, the light thermal inertia structure cold storage which is put into operation rapidly has been and is developing rapidly and forming scale. The enclosure structure of the new type of thermal inertia structure cold storage such as composite wall and roof panel (1.5 < $d < 4$) has high cost, small heat storage coefficient, small total attenuation, and only 3-4 hours delay time. After shutdown, the temperature in the cold storage increases rapidly, and the 0℃ cold storage fruit storage, which requires little storage temperature fluctuation, has great adverse factors. For the thermal insulation design of light structure cold storage, although the standard adopts the method of correction coefficient, it is basically a steady-state method, which may also lead to great errors or even errors, and the fluctuation of storage temperature will inevitably produce large fluctuations; For the thermal inertia cold storage with little requirement for room temperature fluctuation of refrigerated goods, the method of adding correction coefficient on the basis of steady-state calculation can not get the dynamic heat transfer load data required by the energy-saving design of continuous automatic control regulation; For the condition design of traditional heavy thermal inertia and medium thermal inertia cold storage which does not require energy-saving control, the method of simplified calculation of steady-state heat transfer is still barely feasible, but the process design of energy-saving operation of cold storage with continuous automatic regulation and energy-saving control as the key technology is also unable to be realized on the basis of steady-state heat transfer calculation.

It can be seen that the selection of outdoor meteorological parameters for the design and calculation of the cold storage enclosure does not reflect the dynamic characteristics of outdoor air temperature and solar radiation; moreover, if the thermal insulation design of the cold storage room is still adopted, it will lead to a great error or even a wrong steady-state heat transfer calculation method in the enclosure design of the light thermal inertia cold storage; In fact, for all refrigerators of light, medium and heavy thermal inertia structures, this calculation method is not conducive to maintaining a fixed temperature through automatic adjustment, nor to providing dynamic basic data for the design of refrigerators based on continuous automatic adjustment and energy-saving control of dynamic real-time load of the whole system. The heat insulation design method of cold storage enclosure based on dynamic heat transfer proposed in this paper provides a more accurate and practical engineering algorithm for the calculation
of dynamic load of cold storage enclosure, and preliminarily solves all the above problems, which is not only conducive to maintaining a fixed temperature through automatic regulation, but also for continuous automatic regulation and saving of dynamic real-time load based on the whole system be able to control and provide basic data.

3. Analysis and calculation method of wall dynamic heat transfer

3.1. Heat transfer mathematical model of composite wall

The heat is transferred from one side of the cold storage enclosure to the other, forming a thermal system, which are partial differential equations and boundary conditions. Based on the heat exchange theory, when the thickness is far less than the length and width of wall, there is one-dimensional unsteady heat transfer in the wall.\[3][4]

\[
\frac{\partial t(x, \tau)}{\partial \tau} = \frac{\partial^2 t(x, \tau)}{\partial x^2},
\]

\[
q(x, \tau) = -\lambda \frac{\partial t(x, \tau)}{\partial x}
\]

\( t(x, 0) = 0 \)

The basis thought of thermal instantaneous response factors method\[5\] is three main steps, the process of which is: the disturbing quantity curve is dispersed in order of time of unit disturbing quantity; Solve response factors that is the response of wall thermal system to unit disturbing; worked out the air conditioning cooling load temperature and the dynamic thermal basic data by superposing and integrating the response factors of wall.

For example, when calculate thermal instantaneous response factor \( Y(j) \), among which, \(-\alpha_i\) is the root of \( B(s) = 0 \), when \(-\alpha_i\) is not greater than \((-40)\), we can assure satisfactory precision.

\[
Y(0) = K + \sum_{j=1}^{\infty} \frac{B_j}{\Delta \tau} (1 - e^{-\alpha_i \Delta \tau}), \quad j = 0
\]

\[
Y(j) = -\sum_{j=1}^{\infty} \frac{B_j}{\Delta \tau} (1 - e^{-\alpha_i \Delta \tau})^2 e^{-(j-1)\alpha_i \Delta \tau}, \quad j \geq 1
\]

The disturbing quantity curve is dispersed in order of time of unit disturbing quantity, response of which active thenceforward over a long period of time. So we must worked out the air conditioning cooling load temperature and the dynamic thermal basic data by superposing and integrating the response factors of wall. For instance, the formulas for calculating the air conditioning cooling load temperature \( t_l(n, k) \) is as follows:

\[
t_l(n, k) = \sum_{j=1}^{50} Y(j) \theta_2(n - j, k)
\]

\( \theta_2(n - j, k) \) is outdoor air synthetic temperature, \( k \) is orientations of the wall, \( n \) is a given time for calculating, discrete time is \( \Delta \tau = 1h \), at the suggestion of ASHRAE, \( j \) is from 0 to 50.

3.2. Physical property parameter of material

Walls in building are multilayer structure built up of different material, whose physical property parameter involve density \( \rho \), coefficient of thermal conductivity \( \lambda \) and specific heat \( c_p \), which derive from the current code for design of cold storage in China.

4. Calculation process of dynamic cooling load of wall in cold storage
4.1. Example data

According to the current code for design of cold storage in China, the heat transfer coefficient of convective heat transfer surface on the outer surface of the cold storage enclosure is taken as the value of the outer surface of the roof and the outer wall without wind proof facilities, the outer surface coefficient of convective heat transfer is 21 W/m²·℃. The surface heat transfer coefficient of convective heat transfer on the inner surface of the enclosure structure of the cold storage shall be taken as the value when there is a cooling device with air blast in the frozen substance cold storage storage, the inner surface coefficient of convective heat transfer is 12 W/m²·℃.

An example is a cold storage with a design temperature of 10℃ in Beijing, the average temperature of Beijing summer air conditioning is 29.6 ℃, the external wall is prefabricated reinforced concrete external wall, thickness is 240mm, thermal conductivity is 1.15 W/(m·℃), density is 2400kg/m³, specific heat is 0.84kJ/kg·℃. Thickness of polyurethane insulation board inside is 60mm, thermal conductivity is 0.024 W/(m·℃), density is 50kg/m³, specific heat is 1.38×10³ kJ/kg·℃. The absorption rate of outer surface of enclosure to solar radiation is 0.7 according to article 7.2.7 of code for design of heating ventilation and air conditioning of civil buildings (GB50736-2012). The calculation method of wall cooling load is as follows.

$$ CL_w = KF(t_{wi} - t_n) $$

- **CLₜ** — Hourly cooling load formed by wall heat transfer (W)
- **K** — Heat transfer coefficient of wall (W/m²·K)
- **F** — Heat transfer area of wall (m²)
- **tₜ** — Calculation temperature of hourly cooling load of wall (℃)
- **tₙ** — Indoor design temperature in summer (℃)

The value of indoor design temperature of cold storage is 10℃, the heat transfer coefficient of the wall is calculated by the program and then substituted into the formula, and the calculation temperature of hourly cooling load of wall is calculated by the program and then substituted into the formula. According to the code for design of heating ventilation and air conditioning of civil buildings (GB50736-2012), the hourly comprehensive temperature of outdoor air conditioning in summer is calculated, which is used to substituted into the formula and calculate the hourly cooling load of the wall, the calculation method is as follows.

$$ t_{zs} = t_{sh} + (\rho J / h_w) $$

- **tₚ** — Hourly comprehensive temperature of outdoor air conditioning in summer (℃)
- **tₚ** — Hourly temperature calculation of outdoor air conditioning in summer (℃)
- **ρ** — The absorption rate of the external surface of the wall for solar radiation, taken as 0.7
- **J** — Hourly total solar irradiance of wall, W/m²
- **h_w** — Heat transfer coefficient of external surface of wall, (W/m²·℃)

$$ t_{sh} = t_{wp} + \beta \Delta t_r $$

$$ \Delta t_r = \frac{t_{wg} - t_{wp}}{0.52} $$

- **tₚ** — Calculate the daily average temperature outside the air conditioning room in summer, and check the data is 29.6℃;
- **β** — Hourly variation coefficient of outdoor temperature
- **Δtᵣ** — Daily range of outdoor calculated average temperature in summer (℃)
- **tₚ** — Calculated daily dry bulb temperature of outdoor air conditioner in summer (℃)
By inputting the above data into the calculation program compiled according to the reaction coefficient method, the calculation temperature of hourly cooling load of the wall can be obtained, and then the cooling load of the wall can be obtained.

4.2. Example calculation results

Table 1. Cooling load data sheet for the wall of cold storage per square meter

| time | S   | SW  | W   | NW  | N   | NE  | E   | SE  | H   |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0    | 5.73| 6.27| 6.47| 6.08| 5.46| 5.58| 5.77| 5.78| 7.09|
| 1    | 5.61| 6.07| 6.24| 5.91| 5.37| 5.48| 5.65| 5.66| 6.80|
| 2    | 5.50| 5.90| 6.05| 5.75| 5.29| 5.39| 5.54| 5.55| 6.56|
| 3    | 5.40| 5.75| 5.88| 5.62| 5.21| 5.31| 5.44| 5.45| 6.34|
| 4    | 5.32| 5.62| 5.74| 5.51| 5.15| 5.24| 5.36| 5.36| 6.15|
| 5    | 5.25| 5.51| 5.61| 5.40| 5.09| 5.17| 5.28| 5.28| 5.99|
| 6    | 5.18| 5.42| 5.50| 5.31| 5.04| 5.11| 5.22| 5.22| 5.85|
| 7    | 5.19| 5.39| 5.47| 5.30| 5.18| 5.53| 5.66| 5.44| 5.91|
| 8    | 5.23| 5.42| 5.48| 5.33| 5.29| 5.99| 6.22| 5.82| 6.16|
| 9    | 5.33| 5.47| 5.53| 5.40| 5.35| 6.39| 6.80| 6.28| 6.60|
| 10   | 5.57| 5.56| 5.61| 5.49| 5.45| 6.65| 7.27| 6.75| 7.17|
| 11   | 5.89| 5.66| 5.71| 5.60| 5.56| 6.74| 7.56| 7.15| 7.82|
| 12   | 6.24| 5.81| 5.81| 5.71| 5.67| 6.70| 7.63| 7.41| 8.46|
| 13   | 6.58| 6.13| 5.90| 5.81| 5.77| 6.67| 7.48| 7.51| 9.07|
| 14   | 6.86| 6.54| 6.22| 5.91| 5.87| 6.64| 7.36| 7.42| 9.56|
| 15   | 7.03| 7.00| 6.68| 6.12| 5.94| 6.61| 7.23| 7.29| 9.91|
| 16   | 7.07| 7.40| 7.20| 6.46| 5.98| 6.57| 7.11| 7.16| 10.07|
| 17   | 6.95| 7.69| 7.68| 6.84| 5.99| 6.49| 6.96| 7.01| 10.00|
| 18   | 6.80| 7.80| 8.02| 7.17| 6.04| 6.40| 6.81| 6.85| 9.73|
| 19   | 6.62| 7.71| 8.11| 7.33| 6.09| 6.28| 6.63| 6.67| 9.30|
| 20   | 6.40| 7.35| 7.69| 7.01| 5.93| 6.11| 6.42| 6.45| 8.73|
| 21   | 6.21| 7.04| 7.34| 6.75| 5.80| 5.96| 6.23| 6.25| 8.24|
| 22   | 6.03| 6.75| 7.02| 6.51| 5.68| 5.82| 6.06| 6.07| 7.80|
| 23   | 5.87| 6.49| 6.72| 6.28| 5.57| 5.70| 5.91| 5.92| 7.42|

5. Conclusion

The method given in this paper not only considers the common influence of hourly change of outdoor air temperature and hourly change of solar radiation on the wall cooling load, but also fundamentally uses the dynamic heat transfer method to calculate the heat storage effect of the wall. The obtained wall cooling load is the real and accurate instantaneous cooling load introduced into the room hourly, which is a very practical dynamic negative wall of the cold storage Load engineering algorithm, which will provide reliable basic data for the continuous automatic regulation and energy-saving control of the whole system dynamic load of the cold storage.

It can be seen from the data in the table that even if the effect of solar radiation on the wall is considered on the basis of the influence of outdoor air temperature on the wall cooling load, that is to say, the comprehensive temperature of outdoor air is used as the input of external disturbance to start the calculation, the overall heat flow obtained is much smaller than the heat flow calculated according to the current code insulation, and the maximum value of heat flow is also much smaller than that calculated according to the current code insulation, the heat flow is much smaller, which in itself embodies energy conservation.

The method presented in this paper can also be applied to the design and verification of the thickness of the thermal insulation layer in the wall system of the cold storage. The maximum limit value of the
cooling load calculated from the input data can be set, and the appropriate thickness of the thermal insulation layer can be calculated by trial. The design of the thickness of the thermal insulation layer is completely based on the dynamic heat transfer, and the result is accurate and reliable.

The method given in this paper can even be applied to the analysis of wall condensation. The temperature of different positions of each layer of material can be calculated by the software program of reaction coefficient method. As long as the temperature is checked to be higher than the dew point temperature, the space limit is not detailed.

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