Improving the energy efficiency of dynamic air condition systems in buildings with controlled resistance to window heat transfer

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Abstract. This study features energy efficient designs for windows with heat reflecting screens developed by authors that are highly resistant to heat transfer. The use of dynamic air condition systems in industrial buildings, resulting in significantly increased labour productivity, as well as the proposed energy saving measures such as lowering the ambient temperature during non-working hours after preliminary air drying, and the use of window screens, permits lower production costs. Based on these studies, a mathematical model of providing dynamic air conditions in industrial buildings, featuring controlled resistance to heat transfer in windows equipped with heat reflecting screens, has been developed. A formula is given for determining the minimal indoor temperature during standby heating mode, assuming no condensation is allowed on window inner surfaces. To determine the energy efficiency of using heat reflecting window screens in systems intended to maintain dynamic air conditions, changing outdoor air temperatures for an industrial facility located in Moscow were simulated. This study shows that resistance to heat transfer in the translucent part of a window varies significantly during 24 hours not only as a result of using screens, but also due to changing indoor and outdoor air temperature differences.

1. Introduction

Currently, the costs of heating, ventilation, air conditioning and hot water supply in the Russian Federation amount to about 160 million tons of reference fuel per annum (20% of the country’s fuel and energy balance). 80% of the above costs are accounted for by heating [1].

Pursuant to Russian legislation, annual specific consumption of energy in buildings as of 1 January 2020 shall be reduced by 40% of the basic level.

Current Russian energy efficiency regulations stipulate strict requirements regarding annual energy source consumption, including coefficients of resistance to heat transfer through translucent structures. European Union legislatures stipulate a coefficient of heat transfer resistance for windows by 2020 of $1.67 - 2.0 \, (m^2 \cdot ^\circ C)/W$, while Russian official bodies stipulate $1.0 - 1.05 \, (m^2 \cdot ^\circ C)/W$ by 2016.

Maintaining air condition parameters that enhance industrial labour productivity with minimal energy costs is one of the major instruments for reducing production costs.

In industries characterised by monotonous and stressful work, stable indoor environment conditions lead to increased fatigue among personnel and lower labour efficiency. A dynamic indoor environment system (DIE), which increases capacity for work by stimulating the central nervous system, supplies air with parameters that constantly change with time.
2. Dynamic air conditions in an industrial building with controlled resistance to heat transfer through windows

Researchers from Ivanovo State Power Engineering University (ISPEU) developed [2] a mathematical model of dynamic air conditions in an industrial building permitting computation of load schedules for air conditioning systems, taking into account dynamic functioning of the building, and developed an algorithm for realising the dynamic air conditions model in a computer. This mathematical model of dynamic air conditions [2] does not take into account time changes in resistance to heat transfer of new, innovative window designs featuring heat reflecting screens.

The scientists from ISPEU, Scientific and National Institute of Applied Sciences in Strasbourg (INSA de Strasbourg) developed and patented window designs with roll (figure 1), panel (figure 2) and louvre type heat-reflecting screens, which are made of metal and significantly reduce heat losses. The use of screens is desirable during nighttime or in the absence of people.

Figure 1. Window structure with a heat reflecting total metal opaque screen: 1 – body; 2 – pulley; 3 – guide; 4 – heat reflecting screen; 5 – spring; 6 – control wire.

Figure 2. Double panel heat reflecting screen: 1 – aluminium foil; 2 – remote strips.

It was experimentally proved (by natural experiment and numeric simulation) [3] that windows with heat reflecting screens envisage not only significant stepped control of heat transfer resistance \( R_0 \) by raising and lowering of screens, but also, as shown by our simulation data (figure 3), because the given heat transfer resistance to a large extent depends on the difference between indoor and outdoor air temperatures \( \Delta T \): the more installed screens, the more this dependence manifests itself.

The maximum resistance is obtained with the minimum temperature difference and the minimum speed of the outside air. Thus, the resistance to heat transfer for windows with heat-reflecting screens is a nonlinear dependence.

Based on our studies [3], we developed a mathematical model of dynamic air conditions for an industrial building with controlled heat transfer resistance in windows with heat reflecting screens (figure 4).
Figure 3. Dependence of the resistance to heat transfer $R$ of the central zone of window when using the multiple glass unit (MGU) by the formula $4M1\times10x4M1\times10x4M1$ and installed outside 1 – one metal screen; 2 – two screens; 3 – three screens.

Figure 4. System for maintaining of technological microclimate for buildings with adjustable resistance windows: 1 – production room; 2 – wall; 3 – window with a panel-type heat-reflecting screen; 4 – conditioner; 5 – air distributor; 6 – production equipment; 7 – staff; 8 – lighting fixtures.

3. Determining minimal indoor air temperature
To use the potential for lowering air temperatures during non-working hours we determined its minimal value (assuming the need to prevent condensation on the inner surfaces of guard structures).

To determine the dependence of minimal indoor air temperature in standby heating mode on indoor and outdoor air parameters we prepared an equation for heat flux $q$, W/m$^2$ through a window with heat reflecting screens:
in window

\[ q = \frac{t_{in} - t_{out}}{R_{window}} = \alpha_{in} \cdot (t_{in} - \tau_{surf}) \]

where \( t_{in}, t_{out} \) – indoor and outdoor ambient temperature, \(^\circ\)C; \( R_{window} \) – heat transfer resistance of window translucent area, \((m^2\cdot{W})/C\); \( \alpha_{in} \) – coefficient of heat transfer from indoor air to glass, \( W/(m^2\cdot{W}) \); \( \tau_{surf} \) – temperature of indoor window surface, \(^\circ\)C.

In the course of mathematical transformations, it was deduced that minimal indoor ambient temperature in setback heating mode may be determined by:

\[
\begin{align*}
    t_{in, \text{marg}} &= \frac{\tau_d \cdot \alpha_{in} \cdot R_{window} \cdot \theta_{out}}{\alpha_{in} \cdot R_{window} - 1} + \Delta t_{\text{marg}}
\end{align*}
\]

where \( \tau_d \) – dew-point temperature at working hour ambient conditions, \(^\circ\)C; \( \Delta t_{\text{marg}} \) – temperature margin for preventing condensation, \(^\circ\)C.

Indoor air temperature in standby heating mode will be lowered by reducing the amount of heat supplied to inflowing air in the air conditioner heater.

Since dew point temperature largely depends on indoor humidity, we proposed to first dry the air inside the building prior to changing over to standby heating mode to reduce \( t_{in, \text{marg}} \) (see figure 5) by mixing with the outdoor air. This drying method will not result in additional electric power costs, and will also permit renewal of indoor air by outdoor air.

\[ \text{Figure 5. Process of reducing air humidity} \]

\[ d \text{ and temperature} \ t \text{ during standby heating mode using an air conditioning system} \]

\[ \text{(with recirculation) during the cold season (} \ h \text{ – air enthalpy).} \]

4. Results of simulation

To determine the energy efficiency of using heat reflecting window screens in systems for maintaining dynamic air conditions we simulated changes in outdoor air temperature for an industrial building located in Moscow (figure 6 – 8). For reference purposes we took a multiple glass unit (MGU) 4M1x10x4M1x10x4M1 window. The desired pattern of changing indoor air temperature during working hours envisages temperature fluctuations from a minimal value of 18.5\(^\circ\)C to a maximum of 23.5\(^\circ\)C (temperature amplitude \( A_{\text{indoor}} = 2.5 \)\(^\circ\)C), with set mean temperature \( t_{pdac} = 21 \)\(^\circ\)C (\( pdac \) – permissible dynamic air conditions).

As may be seen from the chart showing temperature changes during a 24-hour day (figure 6), indoor air temperature during working hours changes according to the sinusoidal law, while outside working hours the minimal ambient temperature falls to 8.1\(^\circ\)C, and to –5.3\(^\circ\)C in the case of dried air.
Resistance to heat transfer in the translucent part of a window (figure 7) not only differs significantly over a whole day (relative to the reference resistance value $R_0 = 0.47 \text{ (m}^2\text{K)/W}$) not only due to the use of window screens, but also changes because of the varying difference between indoor and outdoor air temperatures $\Delta t$.

![Figure 6](image6.png)

**Figure 6.** Changes in indoor and outdoor air temperatures during a 24-hour day: 1 – reference indoor air temperature ($t_{i,b} = t_{p,ac} = 21^\circ C$); 2 – temperature reduced to $t_{s,b} = 12^\circ C$; 3 – the same, with $t_{s,b}$ reduced to the lowest possible temperature assuming need to prevent condensation; 4 – the same, with preliminary air drying.

![Figure 7](image7.png)

**Figure 7.** Changes in given resistance to window heat transfer $R$ during 24 hours: 1 – reference value; 2 – using screens at night; 3 – using screens with ambient temperature lowered to $t_{s,b} = 12^\circ C$; 4 – using screens at minimal indoor air temperature $t_{i,b, min}$; 5 – the same with preliminary drying; $t_{out}$ – chart showing changing outdoor air temperature.

For multiple glass unit (MGU) windows without screens (chart 1, figure 7), heat transfer resistance in time will be constant. As soon as a window features a heat reflecting screen, resistance to its heat transfer begins to significantly depend on indoor and outdoor air temperature, therefore in figure 7 we may observe during non-working hours 4 variations of changes in resistance $R_0$ (charts 2-5). Maximum
resistance to window heat transfer, equal to 1.93 (m²°C)/W, is achieved with the use of screens at minimal indoor air temperature (following preliminary drying).

![Figure 8](image)

**Figure 8.** Changing heat losses $Q$ through 1 m² of window surface during a 24-hour day:

- 1 – reference;
- 2 – with temperature falling to $t_{s.b}=12$ °C;
- 3 – using screens at night;
- 4 – using screens with temperature lowered to $t_{s.b}=12$ °C;
- 5 – using screens with minimal indoor air temperature $t_{s.b.min}$;
- 6 – using screens, $t_{s.b.min}$ with air drying; $t_{out}$ – outdoor air temperature chart.

Ongoing transmission heat losses per square meter of window glass surface (figure 8) also clearly demonstrate the energy efficiency of both lowering ambient temperature during non-working hours (chart 2), and using screens (chart 3). Using screens in combination with lower indoor air temperature (charts 4 – 6) leads to a further reduction in current heat losses. Maximum heat losses, equal to 70 W/m², are achieved in the reference version (chart 1) at night, at minimal outdoor air temperature. The use of screens with preliminary air drying and lowering of indoor air temperature to the minimal level, current heat losses are reduced to 9 W/m², that is, more than 7 times.

5. Conclusion

Our mathematical model of dynamic air conditions in industrial buildings with controlled resistance to window heat transfer, taking into account the non-linear dependence of translucent structures on indoor and outdoor air parameters and changing window structure during a 24-hour day, enables us to determine the efficiency of using heat reflecting screens and further lowering of ambient temperature during non-working hours. Our method of determining minimal indoor air temperature, assuming the need to prevent condensation on window inner surfaces, enables us to set a desired pattern of ambient air temperature changes to maintain necessary dynamic air condition parameters, taking into account the enhanced properties of windows equipped with screens.

References

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