Investigation of heat and mass transfer processes during film flow around ice surfaces with a phase transition to create a new generation of ice banks

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1. Relevance

Cooling of food processing facilities with a high degree of uneven heat load distribution

**Benefits of ice bank**

1. Reduction of capital costs for refrigeration equipment
2. Reducing energy costs when using the night rate
3. The total refrigerating capacity of the refrigeration park is significantly lower than $Q_{max}$ - the maximum heat load

**Cooling without ice bank**

1. High equipment cost
2. High electricity price during daytime operation
3. The total refrigerating capacity of the refrigeration units should be equal to $Q_{max}$ - the maximum heat load

Typical daily distribution of heat load at a grassroots dairy enterprise

Typical daily distribution of heat load at an industrial dairy enterprise

**REFRIGERATION**
The main disadvantage of this type of ice banks is the low heat transfer coefficient when ice is melted in a large volume

\[ \alpha = 300 \sim 500 \text{ W/(m}^2\text{C)} \]

Problems to be solved:
- development of an experimental stand
- development of research methods
- experimental research
- determination of the influence of the flow rate and temperature of the supplied water on the efficiency of heat and mass transfer
- processing of experimental data and analysis of the results.

Water ice

Volumetric melting ice bank

Water ice

Volumetric ice bank discharge process

The purpose of research is to study the processes of heat and mass transfer during film flow around ice structures with a phase transition to create heat exchangers of a new generation with a high efficiency of heat removal, coupled with the graph of the current heat load.
3. Advantages of film melting

- **Film flow without phase transition**
  - Application: Spray-type heat exchangers
  - Feature: High efficiency of heat transfer
  - Existing dependencies:
    \[ \alpha = a \frac{\Gamma^{0.257}}{H^{0.05}} (1 + bt) \ (Ploege) \]
    \[ \alpha = 40 \frac{\Gamma^{0.4}}{d^{0.6}} \ (Adams) \]
    \[ \alpha = 122l^{0.4} \ (Semilet) \]
  - \( \alpha > 5000 \ W/(m^2 \cdot ^\circ C) \)

- **Volumetric melting**
  - Application: Volumetric melting ice banks
  - Feature: Phase transition of ice in the volume of liquid
  - \( \alpha = 300 \sim 500 \ W/(m^2 \cdot ^\circ C) \)

- **Film flow around melting surfaces**
  - Application: Film Ice banks
  - Feature: High efficiency of heat exchange + phase transition of ice
  - Existing dependencies: ?
  - \( \alpha = 7000 \ W/(m^2 \cdot ^\circ C) \)
4. Results of the literature review

Data obtained in the study of horizontally separated flow around coaxially located cylindrical ice surfaces.

Sketch of a film coaxial ice bank

t_{out} = const

Main operating parameter

$$\Gamma_v = \frac{G}{2 \cdot \Pi} \left( \frac{m^2}{s} \right)$$

$G$ – flow rate ($\frac{m^3}{s}$)

$\Pi$ – linear perimeter m

Thermal balance for a cooled fluid flow

$$\frac{m_{bi} \cdot C_{pi} \cdot (t_{ini} - t_{outi})}{\Delta \tau} = \frac{r \cdot m_{mi} + m_{mi} \cdot C_{pi} \cdot (t_{outi} - t_0)}{\Delta \tau}$$
Scheme of the experimental stand: 1 - Compressor-condensing unit, 2 - Ice bank, 3 - Storage tank, 4 - Pump with frequency changer, 5 – Mass flow meter, 6 - Heater, 7 - Measuring tank, 8 - Filter, 9 - Manometer, 10 - Electronic thermometer, 11 - Regulating valve, 12 - Nozzles, 13 – Data recorder, 14 - Submersible pump, 15 – Shut-off valve, 16 - Flush valve
6. Experimental stand

Film heat exchanger with flat coils (PTA): a) water distribution during irrigation of one section; b) a three-section heat exchanger with water supply through nozzles: pos. 1 - slotted water distributor

Coaxial film heat exchanger

It is necessary to determine:
- Discharged heat Load $Q$
- Heat transfer coefficient $\alpha$

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7. Discharged heat load

Comparative characteristics
Plate heat exchangers: from 12 to 65 kW/m²
Film heat exchanger (FHE): from 120 to 320 kW/m²

Specific heat load [kW/m²]

Range of change of operating parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Regulation range</th>
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<tbody>
<tr>
<td>Water inlet temperature</td>
<td>from 20 °C to 60°C</td>
</tr>
<tr>
<td>Flow rate of water</td>
<td>from 3.2 kg/min to 9.6 kg/min</td>
</tr>
<tr>
<td>Density of irrigation</td>
<td>from 0.5<em>10⁻⁴ m²/s to 1.5</em>10⁻⁴ m²/s</td>
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</tbody>
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Diagrams of heat load distribution between pipes of one FHE section S=0.078 m².
8. Efficiency of heat transfer

The graph of the dependency of the heat load removed by one section of the FHE with a surface $S=0.078 \, \text{m}^2$

Newton-Richman law

\[ q = \alpha (t_{liq} - t_s) \frac{W}{m^2} \]

\( \alpha \) – proportion coefficient

\[ \alpha = f(Re, \Delta t) \]

Dependency of the heat transfer coefficient on the density of irrigation
9. Conclusion

The advantage of the film ice bank has been experimentally proven with respect to the volumetric ice bank:
- the ability to cool water from a temperature of 60 °C to 1 °C in one pass;
- an experimental dependency of the heat transfer coefficient for a film ice bank on the irrigation density has been obtained.

In the investigated range, the values of the heat transfer coefficient are ~22000 W/(m²·°C) reduced to the surface of the heat exchanger and ~7000 W/(m²·°C) in relation to the melting surface, and in ice banks with volumetric melting do not exceed 300 - 500 W/(m²·°C).

Specific heat load of FHE reaches 320 000 W/m², significantly exceeding the same value for plate heat exchangers, which, according to open sources is from 12 000 to 65 000 W/m²

**Fields of application:**
- Dairy industry
- Brewing industry
- Air conditioning
- Emergency and abnormal surges in thermal load
- Cooling of systems with a pulsed heat sources (cooling of lasers, etc.)
Thank you for your attention!
Additional materials

Use of the natural cold of outside air