The Efficiency of Refrigeration Capacity Regulation in the Ambient Air Conditioning Systems

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Abstract. The operation of the ambient air conditioning systems (ACS) is characterized by considerable fluctuations of the heat load in response to the current climatic conditions. It needs the analyses of the efficiency of the application of compressors with frequency converters for refrigeration capacity regulation in actual climatic conditions. A new method and approach to analyzing the effectiveness of ACS cooling capacity adjusting by using the compressor with changing the rotational speed of the motor as an example have been developed, according to which the overall range of changeable heat loads is divided into two zones: the zone of ambient air processing with considerable fluctuations of the current heat load, that requires effective refrigeration capacity regulation by the compressor with frequency converters (from 100% rated refrigeration capacity down to about 50%) and not an adjustable zone of reduced refrigeration capacity below 50% rated refrigeration capacity of the compressor. The magnitudes of threshold refrigeration capacity between both zones are chosen according to the rational value of installed (design) refrigeration capacity on the ACS, required for cooling the ambient air to a target temperature that ensures the maximum annual refrigeration capacity production in actual current climatic conditions. The proposed method and approach to the analysis of the efficiency of the refrigeration capacity regulation of the ACS compressor by distributing the overall range of changes in current heat loads allows increasing the efficiency of utilizing the installed refrigeration capacity in prevailing climatic conditions.

Keywords: Ambient air processing · Stable heat load · Changeable heat load · Threshold refrigeration capacity · Refrigeration capacity distribution

1 Introduction

Significant fluctuations of the heat load characterize the operation of the ambient air conditioning systems (ACS) under the current ambient air temperature t_{amb} and relative humidity φ_{amb} [1, 2]. At the same time, the operation of closed type ACS (processing of indoor air) is characterized by relatively insignificant fluctuations in the heat load on the air coolers (AC), corresponding to changes in the room air temperature within a

V. Ivanov et al. (Eds.): DSMIE 2020, LNME, pp. 343–353, 2020.
https://doi.org/10.1007/978-3-030-50491-5_33

narrow range (about 5 °C). For such closed type ACS it is advantageous to use compressors with frequency converters that provide refrigeration capacity regulation from nominal (rated) to 50% of nominal and lower.

The study aims to develop an approach to the analysis of the efficiency of regulating the refrigeration capacity of an ACS compressor with a frequency converter for actual climatic conditions.

2 Literature Review

In a number of investigations, the air conditioning is considered as one of the technologies for combined cooling, heating, and power (CCHP) [3, 4]. Some of the technical innovations and methodological approaches in waste heat recovery might be applied for traditional refrigeration technologies in air conditioning, in particular, the evaporative cooling [5], two-stage air-cooling, as well as methods to choose rational design value of refrigeration capacity to match current cooling demand [6–8].

Numerous researchers have studied the energy efficiency of the VRF system [9, 10] and proposed some practical recommendations [11, 12]. The simulation results in work [13] show that the VRF systems would save around 15–42% and 18–33% for HVAC site and source energy uses compared to the rooftop unite variable air volume systems (RTU-VAV) systems. The author [14] proposes the method of calculating the thermal load of a building. The VRF systems operate with high part-load efficiency [15, 16], which results in top daily and seasonal energy efficiency. Hence, as ACS typically spend most of their operating hours τ in the range of 40% to 80% of maximum capacity [17]. Results [18] show that ACS have great potential for energy saving, and the adjustability of VRF ACS is better than that of a centralized air conditioning system. The authors [19] study analyzes the cooling load rules of a typical room comparatively under the intermittent and continuous running of ACS.

A combination of the HVAC system with RTU used as the outdoor air processing (OAP) system in the VRF and control strategies to enhance its energy performance and thermal comfort was proposed [10, 20]. The VRF system with energy recovery ventilation (ERV) [21] and a dedicated outdoor air system (DOAS) was introduced [22]. The evaluation of indoor thermal environments and energy consumption of the VRF system [23, 24] with a heat pump desiccant (HPD) was conducted [25].

The HVAC system that processed outdoor air loads by supplying refrigerant from the outdoor unit performed simultaneously as an outdoor unit in the VRF system in contrast with the OAP, which had compressors [26]. In the VRF-OAP system, the multiple indoor units and the OAP were simultaneously connected to an outdoor unit.

The authors [27] developed a control algorithm of the supply air temperature (threshold temperature) in the outdoor air processing (OAP). A higher energy reduction compared with the conventional operation without refrigerant flow regulation, revealed when the outdoor air temperature was closer to the indoor temperature setpoint, was quite evident due to superlative applying the variable speed compressor in part-load modes. The authors [28] on the base of field test results revealed that the actual OAP capacity should be less than 30% of the design outdoor unit capacity to prevent a lack of indoor unit cooling capacities.

3 Research Methodology

In the general case, an overall heat load of any ACS comprises the unstable heat load zone, corresponding to ambient (outdoor) air processing with considerable heat load fluctuations in response to actual climatic conditions, and a comparatively stable heat load zone for subsequent air cooling (subcooling) to a target temperature.

In modern VRF systems, the load modulation is performed by varying refrigerant feed to air coolers. The COP and the specific (per unit of refrigerant mass flow) generated refrigeration capacity are stabilized due to a change in the rotational speed of the piston compressor while reducing the heat load to 50% of the nominal.

Authors developed a methodological approach to the analysis of the efficiency of regulation of the cooling capacity of ACS in actual climatic conditions, according to which the overall range of changes in current heat loads is divided into two zones: a zone of effective regulation of the refrigeration capacity without energy loss and a zone of the reduced not adjustable (unregulated) refrigeration capacity.

For the convenience of calculation for other refrigeration capacities of ACS the heat loads are represented in relative (specific) values per unit air mass flow (G_a = 1 kg/s) – as specific heat load, or refrigeration capacity of a refrigerating machine (RM),

$$q_0 = Q_0/G_a, \mathrm{kJ/kg}, \tag{1}$$

where Q_0 is the total heat load (refrigeration capacity) for airflow G_a.

The rational value $q_{0.\mathrm{rat}}$ of specific refrigeration capacity q_0 on the AC, required for cooling the ambient air to a target temperature of 10 °C, ensures the maximum specific annual refrigeration capacity production $\sum(q_0 \cdot \tau)$ taking into account the actual current climatic conditions [29]. The specific cooling capacity is calculated as follows:

$$q_0 = \xi \cdot c_{\mathrm{ma}} \cdot (t_{\mathrm{amb}} - t_{\mathrm{a2}}), \mathrm{kJ/kg}, \tag{2}$$

where: ξ – coefficient of water vapor condensation heat, calculated as a ratio of the overall heat removed from the air being cooled, including the latent heat of water vapor condensed from the ambient air to the sensible heat transferred; c_a – humid air specific heat. The specific annual refrigeration capacity production

$$\sum(q_0 \cdot \tau) = \sum(\xi \cdot c_a \cdot (t_{\mathrm{amb}} - t_{\mathrm{a2}}) \cdot \tau). \tag{3}$$

The specific refrigeration capacity consumption in the zone of its frequency regulation $q_{0.10/2\mathrm{reg}>0}$ (positive values in the area of adjustable refrigeration capacity from 100 to 50% – above threshold value $q_{0.10\mathrm{rat}}/2$) defined as $q_{0/2\mathrm{reg}>0} = q_0 - q_{0.\mathrm{rat}}/2 \geq 0$, as well as below the range of its frequency regulation $q_{0.10/2\mathrm{reg}<0}$ (positive values in the unregulated range of refrigeration capacity below 50% – below $q_{0.10\mathrm{rat}}/2$): $q_{0/2\mathrm{reg}<0} = q_{0\mathrm{rat}}/2 - q_0 \geq 0$. The values of the unused excess of the installed refrigeration capacity: $q_{0.10\mathrm{rat}}/2 - q_{0.10/2\mathrm{reg}>0}$ in the zone of its frequency regulation (above $q_{0.10\mathrm{rat}}/2$), its excess: $q_{0.10\mathrm{rat}}/2 - q_{0.10/2\mathrm{reg}<0}$ outside the range of its control (below

$q_{0.10\mathrm{rat}}/2)$, the total expenditures of increasing consumption $\sum\left(q_{0.10/2\mathrm{reg}\,>\,0}\cdot\tau\right)=\sum\left[\left(q_{0.10}-q_{0.10\mathrm{rat}}/2\right)\cdot\tau\right]\geq 0$ and excess of refrigeration capacity $\sum\left[\left(q_{0.10\mathrm{rat}}/2-q_{0.10/2\mathrm{reg}\,>\,0}\right)\cdot\tau\right]=q_{0.10}-q_{0.10\mathrm{rat}}/2\geq 0$ in the zone of its regulation (above $q_{0.10\mathrm{rat}}/2$) and consumption $\sum\left(q_{0.10/2\mathrm{reg}<0}\cdot\tau\right)=\sum\left[\left(q_{0.10\mathrm{rat}}/2-q_{0.10}\right)\cdot\tau\right]\geq 0$ and excess of installed refrigeration capacity $\sum\left[\left(q_{0.10\mathrm{rat}}/2-q_{0.10/2\mathrm{reg}<0}\right)\cdot\tau\right]=\sum\left[\left(q_{0.10}-q_{0.10\mathrm{rat}}/2\right)\cdot\tau\right]\geq 0$ below the range of its regulation (lower $q_{0.10\mathrm{rat}}/2$).

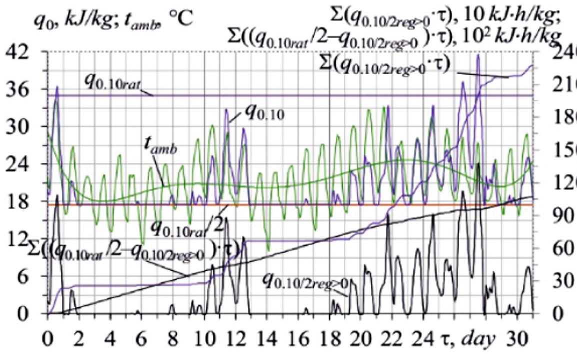
4 Results

For the climatic conditions of the south of Ukraine, when the air is cooled to t_{a2} = 10 °C, the maximum specific annual refrigeration capacity production $\sum\left(q_0\cdot\tau\right)$ takes place at the specific refrigeration capacity $q_0\approx$ 34 kJ/kg as rational $q_{0.\mathrm{rat}}$ [29]. Current values of t_{amb}, specific heat loads at the ACS air cooler (AC) $q_{0.10}$, consumption of the specific refrigeration capacity in the zone of its frequency regulation $q_{0.10/2\mathrm{reg}\,>\,0}=q_{0.10}-q_{0.10\mathrm{rat}}/2\geq 0$ (positive values in the area of adjustable refrigeration capacity from 100 to 50% – above threshold value $q_{0.10\mathrm{rat}/}2$ in Fig. 1a and below the range of its frequency regulation $q_{0.10/2\mathrm{reg}\,<\,0}=q_{0.10\mathrm{rat}}/2-q_{0.10}\geq 0$ (positive values in the unregulated range of refrigeration capacity below 50% – below $q_{0.10\mathrm{rat}}/2$ in Fig. 1b) for climatic conditions (Voznesensk, Mykolaiv region, 2015) are shown in Fig. 1.

As Fig. 1 shows, the share of cold production at 50% frequency regulation of the refrigeration capacity is $\sum\left(q_{0.10/2\mathrm{reg}\,>\,0}\cdot\tau\right)/\left(\sum\left(q_{0.10/2\mathrm{reg}\,>\,0}\cdot\tau\right)+\sum\left(q_{0.10/2\mathrm{reg}\,<\,0}\cdot\tau\right)\right)\approx 0,47$, i.e. about 47% of the total monthly amount of cold spent for cooling the air in the range of variation of the current heat load $q_{0.10}$ from 0 to $q_{0.10\mathrm{rat}}$ = 34 kJ/kg. However, with respect to the unused monthly excess of the installed cooling capacity over the expendable for cooling the air $\sum\left[\left(q_{0.10\mathrm{rat}}/2-q_{0.10/2\mathrm{reg}\,>\,0}\right)\cdot\tau\right]=q_{0.10}-q_{0.\mathrm{rat}}/2\geq 0$ in the region of 50% of its frequency regulation, the share of refrigeration capacity monthly production is 2200/(2200 + 10500) ≈ 0,17 (Fig. 1a, i.e., about 17%, and almost half as much (2200/[2 (2200 + 10500)] ≈ 0,087) in the entire range of changes in the current heat load $q_{0.10}$ from 0 to $q_{0.10\mathrm{rat}}$ = 34 kJ/kg for the July.

This indicates, firstly, the presence of significant reserves to increase the efficiency of ACS by using the excess of the installed refrigeration capacity over that consumed for cooling air, in particular, by accumulating it for subsequent consumption, which provides a significant reduction in the installed refrigeration capacity, and secondly, the possibility to use other methods of regulating the refrigeration capacity in addition to changing the speed of the compressor motor, for example, by turning off the cylinders or the compressor itself in the case of several compressors, etc.

If ACS operates in June or August, the efficiency of applying the refrigeration capacity control by changing the rotational speed of the compressor electric motor will be even lower, and taking into account 3–5 times higher cost of compressors with frequency converters, their application for ACS becomes problematic.



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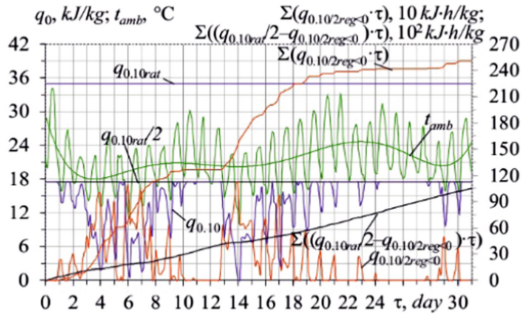
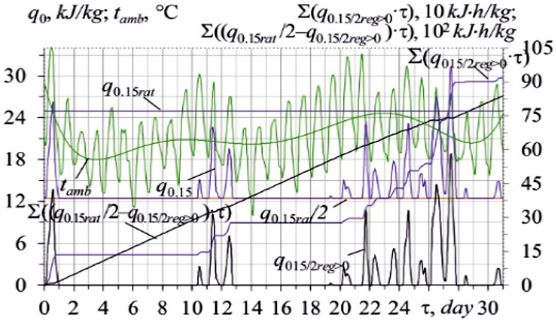


b

Fig. 1. Current values of t_{amb}, refrigeration capacity $q_{0.10}$, consumption $q_{0.10/2\mathrm{reg}>0}$ and unused excess $(q_{0.10\mathrm{rat}}/2 - q_{0.10/2\mathrm{reg}>0})$, total monthly consumption $\sum\left(q_{0.10/2\mathrm{reg}>0}\cdot\tau\right)$ and excess $\sum\left[\left(q_{0.10\mathrm{rat}}/2 - q_{0.10/2\mathrm{reg}>0}\cdot\tau\right)\right]$within frequency regulation (**a**), values of $q_{0.10/2\mathrm{reg}<0}$ and $(q_{0.10\mathrm{rat}}/2 - q_{0.10/2\mathrm{reg}<0})$, $\sum\left(q_{0.10/2\mathrm{reg}<0}\cdot\tau\right)$ and $\sum\left[\left(q_{0.10\mathrm{rat}}/2 - q_{0.10/2\mathrm{reg}<0}\right)\cdot\tau\right]$ below regulation (**b**): $q_{0.10/2\mathrm{reg}>0} = q_{0.10} - q_{0.10\mathrm{rat}}/2 \geq 0$ (adjustable range); $q_{0.10/2\mathrm{reg}<0} = q_{0.10\mathrm{rat}}/2 - q_{0.10} \geq 0$ (unregulated range); threshold value $q_{0.10\mathrm{rat}}/2 \approx 17$ kJ/kg.

When the ambient air is being cooled from t_{amb} to the higher temperatures t_{a2} = 15, 17 and 20 °C, as the cooling temperature t_{a2} rises a significant proportion of the unstable heat load is replaced from its adjustable range ($q_{0/2\mathrm{reg}>0} = q_0 - q_{0.\mathrm{rat}/2} \geq 0$), which falls on the $q_0 \geq q_{0.\mathrm{rat}}/2$, into the range of unregulated heat load $q_0 \leq q_{0.\mathrm{rat}}/2$ (Fig. 2, 3 and 4).



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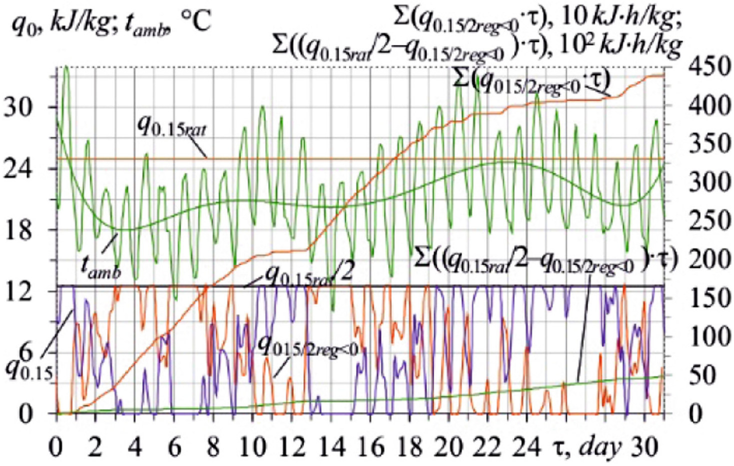
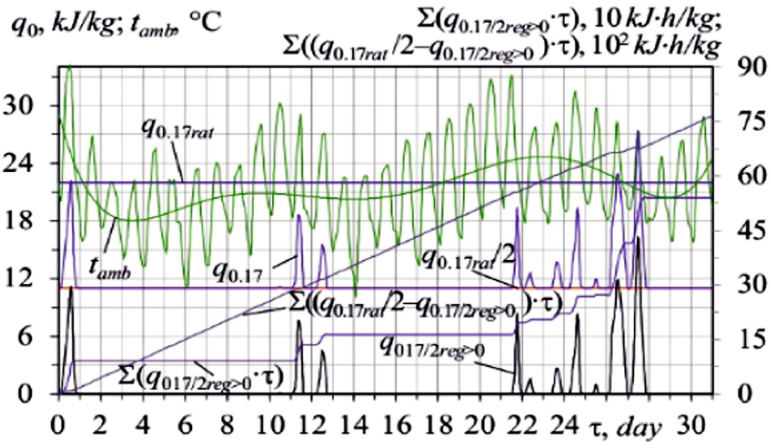


b

Fig. 2. Current values of t_{amb}, specific refrigeration capacity of ACS $q_{0.15}$, consumption of refrigeration capacity $q_{0.15/2\text{reg} > 0}$ and unused excess of installed refrigeration capacity ($q_{0.15\text{rat}}/2 - q_{0.15/2\text{reg} > 0}$), the total monthly consumption $\sum\left(q_{0.15/2\text{reg} > 0} \cdot \tau\right)$ and excess $\sum\left[\left(q_{0.15\text{rat}}/2 - q_{0.15/2\text{reg} > 0}\right) \cdot \tau\right]$ of refrigeration capacity within frequency regulation (**a**), values of $q_{0.15/2\text{reg} < 0}$ and ($q_{0.15\text{rat}}/2 - q_{0.15/2\text{reg} < 0}$), $\sum\left(q_{0.15/2\text{reg} < 0} \cdot \tau\right)$ and $\sum\left[\left(q_{0.15\text{rat}}/2 - q_{0.15/2\text{reg} < 0}\right) \cdot \tau\right]$ below the range of its regulation (**b**) when cooling the ambient air from t_{amb} to t_{a2} = 15 °C: $q_{0.15/2\text{reg} > 0} = q_{0.15} - q_{0.15\text{rat}}/2 \geq 0$ (adjustable range); $q_{0.15/2\text{reg} < 0} = q_{0.15\text{rat}}/2 - q_{0.15} \geq 0$ (unregulated range); threshold value $q_{0.15\text{rat}}/2 \approx 12$ kJ/kg.

As Fig. 2 shows, the share of the refrigeration capacity monthly production at 50% frequency regulation of refrigeration capacity is: $\sum\left(q_{0.15/2\text{reg} > 0} \cdot \tau\right)/\left(\sum\left(q_{0.15/2\text{reg} > 0} \cdot \tau\right) + \sum\left(q_{0.15/2\text{reg} < 0} \cdot \tau\right)\right) \approx 0,17$, i.e., about 17% of the total monthly amount of the refrigeration capacity expended for cooling the air in the range of variation of the current heat load $q_{0.15}$ from 0 to $q_{0.15\text{rat}}$ = 25 kJ/kg.



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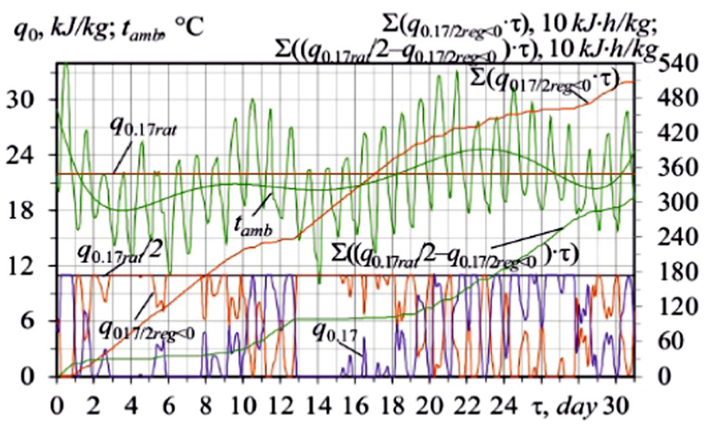

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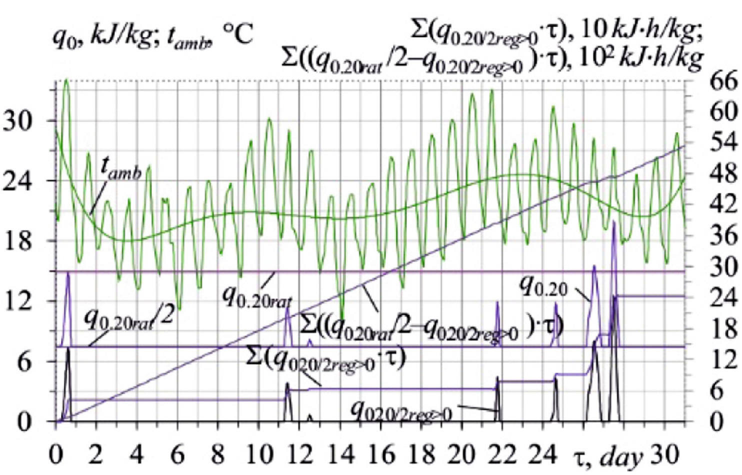
Fig. 3. Current values of t_{amb}, specific refrigeration capacity $q_{0.15}$, consumption $q_{0.17/2\mathrm{reg}>0}$ and unused excess of installed refrigeration capacity ($q_{0.17\mathrm{rat}}/2 - q_{0.17/2\mathrm{reg}>0}$), the total monthly consumption $\sum\left(q_{0.20/2\mathrm{reg}>0}\cdot\tau\right)$and excess $\sum\left[\left(q_{0.17\mathrm{rat}}/2 - q_{0.17/2\mathrm{reg}>0}\right)\cdot\tau\right]$ of refrigeration capacity within frequency regulation (**a**), values of $q_{0.17/2\mathrm{reg}<0}$ and ($q_{0.17\mathrm{rat}}/2 - q_{0.17/2\mathrm{reg}<0}$), $\sum\left(q_{0.17/2\mathrm{reg}<0}\cdot\tau\right)$ and $\sum\left[\left(q_{0.17\mathrm{rat}}/2 - q_{0.17/2\mathrm{reg}<0}\right)\cdot\tau\right]$ below the range of its regulation (**b**) when cooling the ambient air from t_{amb} to t_{a2} = 17 °C: $q_{0.17/2\mathrm{reg}>0} = q_{0.17} - q_{0.17\mathrm{rat}}/2 \geq 0$ (adjustable range); $q_{0.17/2\mathrm{reg}<0} = q_{0.17\mathrm{rat}}/2 - q_{0.17} \geq 0$ (unregulated range); threshold value $q_{0.17\mathrm{rat}}/2 \approx 11$ kJ/kg.

The share of the refrigeration capacity monthly production at 50% frequency regulation of refrigeration capacity is: $\sum\left(q_{0.17/2\mathrm{reg}>0}\cdot\tau\right)/\left(\sum\left(q_{0.17/2\mathrm{reg}>0}\cdot\tau\right)+\sum\left(q_{0.17/2\mathrm{reg}<0}\cdot\tau\right)\right)\approx 0.093$, i.e. about 9.3% of the total monthly amount of the refrigeration capacity expended for cooling the air in the range of variation of $q_{0.17}$ from 0 to $q_{0.17\mathrm{rat}}$ = 22 kJ/kg (Fig. 3).



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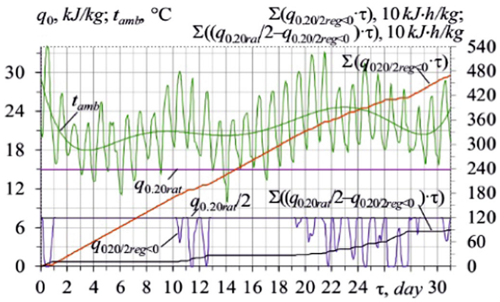

b

Fig. 4. Current values of t_{amb}, consumption of specific refrigeration capacity $q_{0.20/2\mathrm{reg}>0}$ and unrealized excess of installed refrigeration capacity ($q_{0.20\mathrm{rat}}/2 - q_{0.20/2\mathrm{reg}>0}$), the total monthly consumption $\sum\left(q_{0.20/2\mathrm{reg}>0}\cdot\tau\right)$ and excess $\sum\left[\left(q_{0.20\mathrm{rat}}/2 - q_{0.20/2\mathrm{reg}>0}\right)\cdot\tau\right]$ of refrigeration capacity within frequency regulation (**a**), values of $q_{0.20/2\mathrm{reg}<0}$ and ($q_{0.20\mathrm{rat}}/2 - q_{0.20/2\mathrm{reg}<0}$), $\sum\left(q_{0.20/2\mathrm{reg}<0}\cdot\tau\right)$ and $\sum\left[\left(q_{0.20\mathrm{rat}}/2 - q_{0.20/2\mathrm{reg}<0}\right)\cdot\tau\right]$ below the range of its regulation (**b**) when cooling the ambient air from t_{amb} to t_{a2} = 20 °C: $q_{0.20/2\mathrm{reg}>0} = q_{0.20} - q_{0.20\mathrm{rat}}/2 \geq 0$ (adjustable range); $q_{0.20/2\mathrm{reg}<0} = q_{0.20\mathrm{rat}}/2 - q_{0.20\geq 0}$ (unregulated range); threshold value $q_{0.20\mathrm{rat}}/2 \approx 7.5$ kJ/kg.

As Fig. 4 shows, the share of the refrigeration capacity monthly production at 50% frequency regulation of the refrigeration capacity is $\sum\left(q_{0.20/2\mathrm{reg}>0}\cdot\tau\right)/\left(\sum\left(q_{0.20/2\mathrm{reg}>0}\cdot\tau\right)+\sum\left(q_{0.20/2\mathrm{reg}<0}\cdot\tau\right)\right)\approx 0.05$, i.e., about 5% of the total amount of the refrigeration capacity monthly spent for cooling the air in the range of changes in the current heat load $q_{0.20}$ from 0 to $q_{0.20\mathrm{rat}}$ = 15 kJ/kg, which indicates an extremely low efficiency of regulation of ACS refrigeration capacity by the speed of rotation of the piston electric motor compressor and the need for other control methods.

5 Conclusions

A method and approach to the analysis of the efficiency of regulation of the refrigeration capacity of ACS in actual climatic conditions is proposed, according to which the entire range of changes in current heat loads is divided in two zones: a zone of ambient air processing with considerable fluctuations of the current heat load, that requires effective refrigeration capacity regulation by compressor with frequency converters (from 100% rated refrigeration capacity down to about 50%) and a not adjustable zone of the reduced refrigeration capacity below 50% rated refrigeration capacity of compressor. The magnitudes of threshold refrigeration capacity between both zones are chosen according to the rational value of the installed refrigeration capacity on the ACS, required for cooling the ambient air to a target temperature that ensures the maximum annual refrigeration capacity production in actual climatic conditions.

It is shown that for the summer month, the proportion of the refrigeration capacity monthly consumed for cooling the ambient air to the target temperature with a 50% frequency control of the refrigeration capacity is about 10% of its total amount that could be monthly produced at rated load. This fact indicates a low efficiency of regulating the refrigeration capacity of ACS by changing the rotation speed of the reciprocating compressor electric motor and the need for other control methods.

The proposed method and approach to the analysis of the efficiency of the refrigeration capacity regulation of the ACS compressor by distributing the overall range of changes in current heat loads allows revealing the reserves for increasing the efficiency of utilizing the installed refrigeration capacity in prevailing climatic conditions.

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