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A novel degree-hour method for rational design loading

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Abstract

Cooling degree-hours (CDH) received the broadest application in evaluation of the ambient air cooling efficiency in power engineering (engine intake air cooling systems) and air conditioning. The current CDH numbers are defined as a drop in air temperature multiplied by associated time duration of performance and their summarized annual number is used to estimate the annual effect achieved due to sucked air cooling in power plants based on combustion engines (fuel saving, power output increment) and in air conditioning (refrigeration energy generation according to needs). A majority of approaches to designing ambient air cooling systems is proceeding from the cooling capacity of the chillers selected to provide a maximum current or annual CDH number with corresponding maximum current or annual effect (additional energy produced or fuel consumption reduction) in site climate location. But such approaches lead to inevitable oversizing the chillers and cooling systems in the whole. The analysis of intake air cooling efficiency in site varying climatic conditions, accompanied by quite a simple numerical simulation, enabled to reveal the potential of its enhancement and evaluate numerically the results of each step of designing in logical sequence. The new approaches to cooling system rational designing were introduced, that enables to synthesize and substantiate innovative principal decisions to exclude unproductive waste of installed (design) cooling capacity in actual operation. The innovative findings of methodological approaches include the use of the rate of annual CDH number increment as an indicator for selecting the optimum and rational values of design cooling capacity. The optimum cooling capacity corresponds to maximum rate of summarized annual CDH increment and maximum level of thermal loading accordingly, which provides minimum sizes of the chiller. In reality, it is a minimum permissible value of cooling capacity of the chiller installed and the overall ambient air cooling system. The rational cooling capacity, that enables to achieve practically maximum value of annual CDH and avoid chiller oversizing, is determined as the second, local, maximum of the rate in the summarized annual CDH over the range above the first one, global, maximum. A rational design cooling capacity determined by applying the novel methodology allows to decrease the ambient air cooling system sizes by 15 to 20% compared with traditional designing issuing from the peaked thermal load during a year. With this practically a maximum annual effect in fuel saving (energy generation or others) can be achieved too.

Keywords

Cooling, ambient air, degree-hour, design load, cooling capacity, annual effect, chiller

Introduction

Cooling degree-hours (CDH) found the broadest application in evaluation of the ambient air cooling efficiency in power engineering, first of all in engine inlet air cooling systems (engine IACS): as evaporative cooling potential when gas turbine inlet cooling by inlet fogging[1,2] and by chillers[3,4,5], as well as in air conditioning systems (ACS)[6–8] and in trigeneration systems with ACS for cooling combustion engine intake air.[9,10] In order to estimate the IACS operating efficiency over the all range of site climatic conditions, the current CDH numbers are to be summarized to calculate the overall $\sum$CDH number over a considered period (month, year, season) expected in site climatic conditions[11,12] or along route line for transport ACS.[13]

A commonly used analysis involves calculations of the annual $\sum$CDH, while assigning an economic benefit to each CDH number in terms of fuel saved or engine output increased due to cooling.[14,15] This calculation gives the total annual fuel saving or additional power output that can be produced due to engine inlet air cooling[16,17] and takes into account the climatic performance characteristics of the engine applied.

The analyses of cooling load profiles when cooling air at the GT inlet was conducted in dependence of dry and wet bulb ambient air temperatures and humidity.[18,19] The annual $\sum$CDH and cooling load profiles were investigated depending on the ambient temperature and humidity distribution.[18,20,21] A sinusoidal distribution of ambient temperature was proposed.[6,22]

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In reality, any estimation method, used in thermal technologies and issuing from annual (monthly, seasonal) effect, based on the "hour-by-hour" or other time step by step calculation procedure to take into account actual varying site climatic conditions might be considered as based on cooling/heating degree hour (C/HDH) numbers. In the case of IACS or ACS such methods involve CDH calculations in terms of ambient air temperature depression: on the base of ambient dry-bulb,[5,6] wet bulb[1] or both of the temperatures[18] to save energy due to sucked air cooling and performance at rational cooling capacity. The latter is to off set actual cooling requirements in response to actual ambient air parameters and achieve practically maximum annual effect as result.[7,23]

The thermal demand management (TDM)[24,25] are based on different criteria.[9,26] They were developed for combined cooling, heat and power – trigeneration,[27,28] as well as ACS for building applications[29,30] including modern Variable Refrigerant Flow (VRF) systems.[31,32]

In energetic application the cooling potential, needed to cover thermal duties, is to be compared with its available value gained due to waste heat recovery. The latter can be increased through deep recovering waste heat from combustion engines: gas turbines (GT) and engines (GE), internal combustion engines (ICE), A potential of the heat released from internal combustion engines might be enhanced due to deep exhaust gas heat utilization.[11,33] The latter becomes possible due to combustion of waterfuel emulsion that makes possible to apply low temperature condensing surfaces.[13,34,35] Besides, the harmful emissions can be reduced through exhaust gas ecological recirculation.[36] In both cases, the exhaust gas heat can be converted into refrigeration for cooling engine intake air, primary evaluated by cooling degree hour (CDH) numbers. As deeper intake air cooling, id est. higher CDH, the greater effect in engine fuel saving or power augmentation is gained.

The heat gained due to utilization of engine exhaust gas heat might be converted into refrigeration by waste heat recovery chillers (WHRCh) for cooling combustion engine cyclic air that leads to improve engine fuel efficiency.[5] Besides direct evaporative cooling,[37,38] compression refrigeration machines,[39] adsorption refrigeration[40] and absorption ammonia-water chillers[41] or lithium-bromide chillers. The absorption lithium-bromide chillers (ACh) are highly efficient and widespread in a hot climate. The simple cycle ACh have quite high values of COP within 0.7 to 0.8. They are environmentally friendly due to use of water as a coolant. However, because of a comparably increased chilled water temperature of 7°C they are not able to reduce the air temperature less than 15°C.

The most simple in construction refrigerant ejector chillers (ECh) enable to achieve the temperature of air lower than 10°C[42,43] with increased effect (fuel saving, power increase) accordingly. But they have lowered COP of 0.2 to 0.4 and consume increased heat as result. In this case the energy saving technologies as exhaust gas boilers with low temperature condensing surfaces can be applied to arise the available heat for cooling engine cyclic air. For these purposes quite simple jet or thermopressor devices[44] can be used to cool charge air in ICE[12] or compressed air in GT.[45]

So far as the effect, achieved due to cooling sucked air and evaluated by CDH number as a primary criterion, depends on the temperature of cooled air limited by difference between the temperatures of air cooled and coolant at the air cooler outlet accordingly, it could be enhanced by heat transfer intensification. The latter, in its turn, enables deeper air cooling by applying, for instance, the coolants of different temperature (chilled water, boiling refrigerant) in two-stage hybrid air coolers[35,46] fed by coolants from WHRCh of combined types, for instance absorption-ejector chillers (AECh).[10]

In order to increase heat flux at reduced temperature difference in heat exchangers, leading to decrease the sizes of heat exchangers and corresponding energy spent to cover their aerodynamic resistance at lowered leaving temperature of cooled air simultaneously, the various methods of heat transfer intensification[47,48] and advanced heat exchangers[47,49,50] and injector circulation contours[10] are proposed.

In order to enhance and estimate the efficiency of fuel saving technologies based on engine cyclic air cooling the various simulation methods with using ANSYS program complexes,[49,51] methods for processing the data on ambient air parameter influence on AECS loading,[52,53] air temperature and humidity control,[54,55] exhaust energy recovery[56] and economical analysis[57] were applied.

As aforementioned, any estimation method, used in thermal technologies and issuing from annual (monthly, seasonal) effect gained, is based on the "hour-by-hour" calculation of cooling/heating degree hour (C/HDH) numbers procedure to take into account actual varying site ambient air parameters.

Although many scientists consider the cumulative effect, gained due to air cooling, calculated proceeding from CDH along with time elapsed (yearly CDH profile),[18,58] only some studies focus on analysing the character (rate of increment) of yearly cumulative cooling profiles versus thermal load when determining a design cooling load[27,28] and taking into account the rate of cumulative cooling characteristic increment (Radchenko A.et al. 2020.[59])

Practically all typical methods, that include summarizing the CDH number, are based on the approach that a design cooling capacity is to off set maximum requirements within the overall range of yearly operation.[18,19] Such assumption leads to inevitable overestimation of design loads and oversize of the chillers and the IACS in the whole. Thus the problem to define the correct design heat load to avoid significant overestimation and satisfying the closed to maximum cooling requirements simultaneously needs further decision.

The object is to develop easy to use method to define a rational design cooling capacity of IACS, that provides practically maximum annual effect achieved due to cooling and avoids noticeable oversizing simultaneously, and its optimum value, that allows to achieve a maximum rate of summarized effect at minimum sizes, that enables users to conduct appropriate designing of IACS for site climatic conditions.

Research methodology

General assumptions and hypothesis

The following assumptions and approaches for rational designing of IACS basing on cooling degree-hours (CDH) numbers are accepted.

The annual cooling potential as summarized cooling degree-hour numbers $\sum$CDH, previously applied only for estimation of the effect achieved due to cycle air cooling in combustion engines (reduction of fuel consumption, increase in engine power output), is used to define a rational design thermal load on IACS and cooling capacity of the chillers.

The current cooling degree-hour (CDH) number is calculated as a multiplication of two variables: a temperature depression Δt of air being cooled and corresponding operation duration τ: CDH = Δt·τ, °C•h.

The widespread program "meteomanz" (http://www.meteomanz.com) is applied to choose site temperature t_a and relative humidity φ_a of ambient air as real input data for CDH number calculation.

The specific cooling capacity q_0 as the overall cooling capacity Q_0 related to mass flow rate G_a of ambient air, $q_0 = Q_0/G_a$, is used to generalize the results for any thermal load and total cooling capacity and to simplify the procedure of calculations.

The lack of typical methods of IACS designing, based on the current CDH numbers and aimed to cover yearly peak demands, is caused by the variations in actual ambient air temperature depressions $\Delta t = t_a - t_{a2}$ due to its cooling to a set temperature t_{a2} and in thermal loads on IACS as result. These needs the approximation of CDH number characteristic curve with deviations (inaccuracy) of about 20%, that excludes the possibility to define a correct design cooling capacity value proceeding from the current thermal loads in principle and inevitably leads to IACS oversizing.

The following hypothesis are formulated for adopting the current CDH numbers to rational designing of IACS:

– the fluctuations of current CDH numbers and thermal loads on the chillers and IACS accordingly, influenced by changeable ambient air parameters, are preferably to reflect by the rate of their summarized annual cooling degree hour $\sum$CDH increment; – the use of relative value of summarized annual cooling degree hour $\sum CDH/q_0$, referred to design cooling capacity, as an indicator enables to select the optimum value of cooling capacity $q_{0.opt}$ of IACS that provides the maximum rate of summarized annual cooling degree hour $\sum$CDH increment $(\sum CDH/q_0)_{max}$ and minimum sizes of the chillers accordingly, as well as the rational cooling capacity $q_{0.rat}$ providing practically maximum annual $\sum$CDH number and annual effect as result, but without noticeable IACS oversizing.

Calculation procedure

The current cooling degree hour values CDH are calculated as the multiplication of a temperature depression Δt as difference between the ambient air temperatures t_a and a set temperature of chilled air t_{a2} and corresponding operation duration τ:

CDH = Δt·τ, °C•h or K•h, where $\Delta t = t_a - t_{a2}$, oC• or K.

The summation of the current CDH numbers as intake air cooling potential for a year, i.e. ΣCDH = Σ(Δt τ), oC•h or K•h, gives a total annual intake air cooling potential at a location.

The use of cooling degree hour CDH number as a primary criterion allows to evaluate the annual effect gained due to cooling sucked air of combustion engines as the annual fuel reduction by applying quite a simple correlation like

$$\sum B = \sum[\mathrm{CDH}\,(\Delta b_e/\Delta t)\bullet P_e] \tag{1}$$

where b_e – specific fuel consumption of combustion engine, g/(kWh); P_e – engine power output, kW, or as increase in engine power energy output $\sum \Delta P_e$ according to correlation

$$\sum \Delta P_e = \sum[\mathrm{CDH}\,(\Delta P_e/\Delta t)\bullet P_e] \tag{2}$$

With this the values of specific fuel consumption reduction $\Delta b_e/\Delta t$ or increase in engine power $\Delta P_e/\Delta t$ •due to depression of engine sucked air temperature by each 1°C are selected according to engine climatic characteristic.[1,5]

The specific cooling capacity q_0 as the overall cooling capacity Q_0 related to mass flow rate G_a of ambient air, $q_0 = Q_0/G_a$, is used to generalize the results for any thermal load and overall cooling capacity and to simplify the procedure of calculations.

With the aim of generalization of the results and simplifying the calculation procedure, the thermal load and cooling capacity accordingly is used in relative value as a specific cooling capacity q_0, referred to unit air mass flow rate:

$$q_0 = Q_0/G_a,\ \mathrm{kW/(kg/s),\ or\ kJ/kg} \tag{3}$$

where Q_0 is the overall cooling capacity for the total air mass flow rate G_a:

$$Q_0 = c_a\,\xi\bullet\Delta t_a\bullet G_a \tag{4}$$

where $\Delta t_a = t_a - t_{a2}$ – ambient air temperature depression; ξ – specific heat ratio of the overall heat removed from the air to its sensible heat component; c_a – specific heat of air [kJ/(kg·K)].

The optimum cooling capacity corresponds to maximum rate $\sum CDH/q_0$ of summarized annual cooling degree hours ΣCDH increment and maximum level of thermal loading accordingly, which provides minimum sizes of the chiller. In reality, it is a minimum permissible value of cooling capacity of the chiller installed and the overall ambient air cooling system. The rational cooling capacity, that enables to achieve practically maximum value of annual cooling degree hours ΣCDH and avoid chiller oversizing, is determined as the further second, local, maximum rate of summarized cooling degree hours ΣCDH over the range above the first, so called global, maximum.

A method to determine a rational design cooling capacity $q_{0.rat}$ that enables to achieve the annual cooling degree hour $\sum CDH_{rat}$ number closed to its maximum value allows to exclude IACS oversizing due to adding new supplementary stages. The calculation of an optimum specific cooling capacity $q_{0.opt}$, that provides maximum rate $\sum CDH/q_0$ of

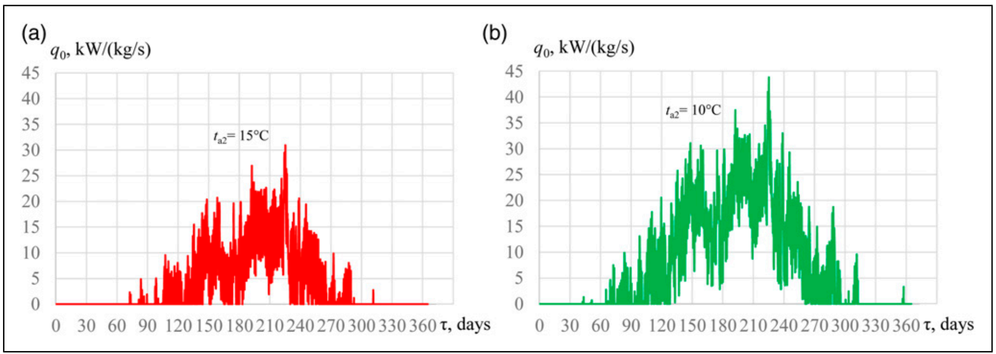

Figure 1. Changes in specific cooling capacities q_0 during 2017: (a) – $q_{0.15}$ for t_{a2} = 15°C; (b) – $q_{0.10}$ for t_{a2} = 10°C.

summarized cooling degree hour ΣCDH increment, is considered as the first addition step. In its turn, the maximum rate $\sum CDH/q_0$ of summarized cooling degree hour ΣCDH increment corresponds to minimum values of cooling capacity, $q_{0.min} = q_{0.opt}$, and sizes of the chiller.

With this the relative value of annual cooling degree hour $\sum CDH/q_0$ as referred to corresponding cooling capacity q_0 is applied as an indicator for maximum rate $(\sum CDH/q_0)_{max}$ of cumulative characteristic CDH= f(q_0) to define optimum values $q_{0.opt}$ and $\sum CDH_{opt}$ accordingly. The values of both $q_{0.opt}$ and $\sum CDH_{opt}$ are significantly lower than their maximum values $q_{0.max}$ and $\sum CDH_{max}$.

A rational cooling capacity $q_{0.rat}$, that allows to achieve the value of annual cooling degree hour number $\sum CDH_{rat}$ closed to its maximum $\sum CDH_{max}$ and avoid chiller oversizing, is determined as the second, local, maximum rate of cumulative characteristic CDH = f(q_0) over the range above the first, global, maximum, $\sum CDH - \sum CDH_{opt}$, id est. beyond $q_{0.opt}$ and $\sum CDH_{opt}$.

With this the relative annual $\sum CDH$ increment is used as indicator:

$$\left[\sum CDH - \sum CDH_{opt}\right] \Big/ q_0 \qquad (5)$$

where $\sum CDH > \sum CDH_{opt}$.

It needs to be noted, that such a considerable reduction in design cooling capacity of installed chiller by 15 to 20% is achieved due to excluding an unproductive waste of installed chiller cooling capacity versus to conventional approach to cover peaked current cooling duties accompanied just a negligible increment in the annual cooling degree hour $\sum CDH$ leading to enlarged value of overestimated design cooling capacity q_0.

Results

Great yearly variations of current specific cooling capacities q_0, required for ambient air cooling to temperatures 10 and 15°C (2017, southern Ukraine, Figure 1) reveal a real problem to select a proper design cooling capacity for chiller and IACS in the whole, that would enable to off set current duties avoiding overestimation.

This is approved by cumulative values of temperature drops Δt, their duration τ and cooling degree hour CDH numbers versus specific cooling capacities q_0 for ambient air cooling to t_{a2} = 10 and 15°C during 2017 in Mykolayiv region are shown in Figure 2.

Cumulative values of cooling degree hour CDH numbers were calculated as CDH = Δt τ, oC•h, where $\Delta t = t_a - t_{a2}$ and τ – hours lapsed in a year at inlet air cooled from ambient temperatures t_a to a target value t_{a2}.

Cumulative characteristics CDH = f(q_0) of ambient air chilling are calculated as summarized samples of CDH = Δt τ, oC•h, at each current specific cooling capacity q_0.

As one can see from Figure 2,c, the closed to maximum values of cumulative cooling degree hour CDH take place within wide ranges of specific cooling capacities q_0: q_0 within 13 to 17 kW/(kg/s) for t_{a2} = 15°C and within 18 to 26 kW/(kg/s) for t_{a2} = 10°C. These lead to considerable uncertainty while defying proper values of design cooling capacity q_0.

The existence of maximum rate of annual cooling degree hour $\sum CDH$ potential, received by summation of all the current CDH numbers on the base of step by step calculations over the total range of q_0, is quite evident (Figure 3).

With this the annual $\sum CDH$ numbers are calculated by summing the differences $\Delta t_a = t_a - t_{a2}$ between the hourly ambient temperatures t_a and set values t_{a2} = 10 and 15°C multiplied by the hours τ lapsed (Figure 3).

A significant fluctuation of cumulative current cooling degree hour CDH numbers over a wide range of q_0 (Figure 3(b)) makes practically impossible to define a proper value of cooling capacity q_0, that would provide a maximum rate of summarized annual cooling degree hour $\sum CDH$ increment, considered as optimal value $q_{0.opt}$.

As it is seen from Figure 3, the values of design cooling capacity q_0 within 33 to 43 kJ/kg, needed for cooling ambient air to 10°C, provides growing summarized cooling potential $\sum CDH$ from 44,000 to 45,000°C•h (closed to a maximum value 46,000°C•h), id est. without noticeable rate of its increment.

It is quite evident, although the rate of summarized $\sum CDH$ numbers increment from 44,000 to 45,000°C•h (for t_{a2} = 10°C) is relatively negligible, the corresponding range of cooling capacities q_0 is still wide: within 33 to 43 kJ/kg or kW/(kg/s), that leads to a large oversizing.

With increasing the set cooled air temperature t_{a2} to 15°C the choice of proper design specific cooling capacity q_0 is more difficult because of uncertainty, so as the behaviour of characteristic curve of annual summarized cooling degree hour $\sum CDH$ = f(q_0) becomes less noticeable (Figure 3).

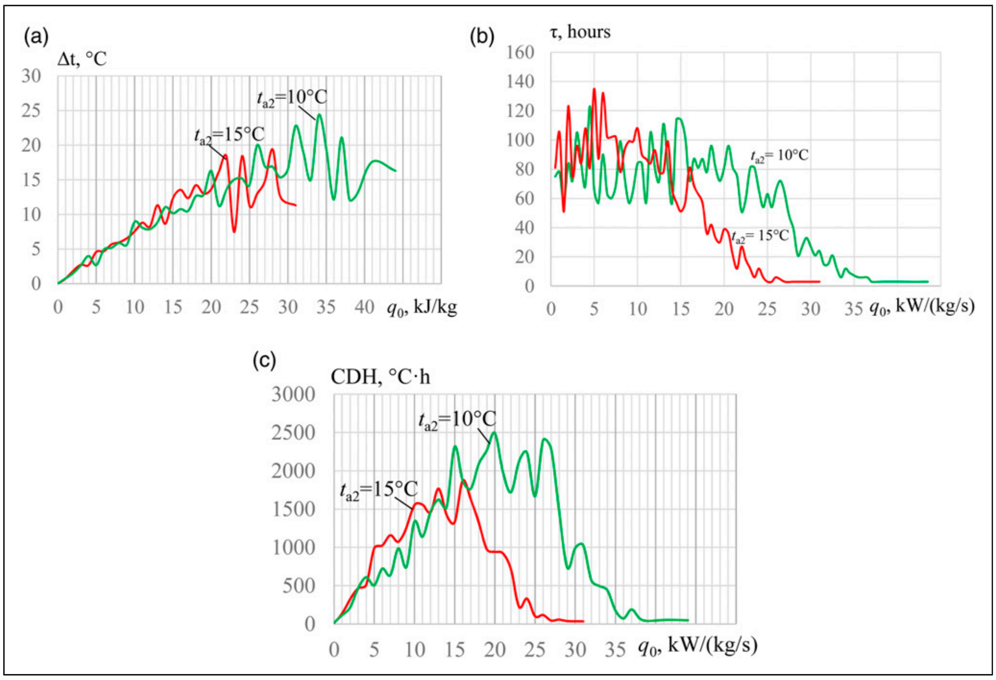

Figure 2. Cumulative values of temperature drops Δt (a) and their duration τ (b) and values of CDH numbers (c) versus specific cooling capacities q_0 for cooling to 10 and 15°C: CDH = Δt τ; Δt = $t_a - t_{a2}$.

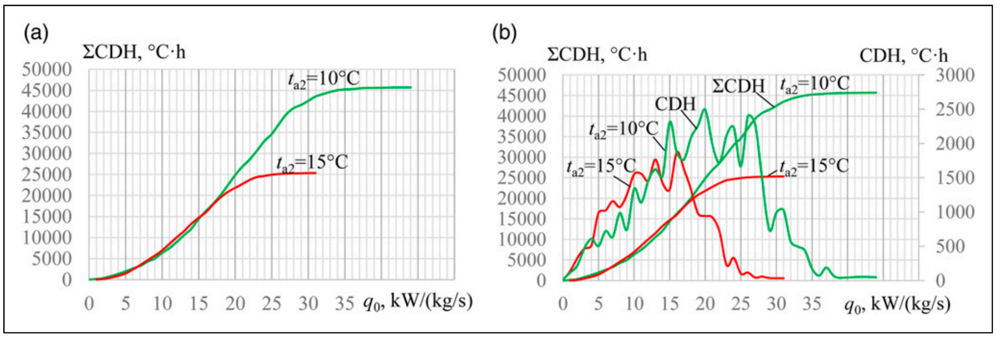

Figure 3. Annual ∑CDH numbers of cooling ambient air to 10°C and 15°C (a) and cumulative current CDH numbers (b) versus corresponding specific cooling capacities q_0.

In order to define a proper design cooling capacity the supplementary stages of methodology, focused to calculate its optimal value $q_{0.opt}$, that makes possible to achieve a maximum rate of summarized cooling degree hour increment ∑CDH/q_0, were added (Figures 4 and 5).

As Figure 4 shows, the optimal value $q_{0.15opt}$ = 18 kW/(kg/s) of cooling capacity, that corresponds to maximum rate of summarized cooling degree hour increment ∑CDH/$q_{0.15}$, and summarized cooling degree hour $\sum CDH_{15opt}$ = 20,000°C•h when air cooling to 15°C, is significantly lower compared to its maximum value $q_0 \approx$ 32 kW/(kg/s) with corresponding $\sum CDH_{15} \approx$ 25,000°C•h. When cooling air to 10°C the optimal value is $q_{0.10opt}$= 28 kW/(kg/s) against its maximum $q_0 \approx$ 44 kW/(kg/s) with corresponding values $\sum CDH_{10}$ = 40,000°C•h against its maximum $\sum CDH_{10} \approx$ 46,000°C•h.

As it is also seen from Figure 4, a developed method enables to calculate precise optimal specific cooling capacities $q_{0.15opt}$ =18 kW/(kg/s) required for t_{a2} = 15°C and $q_{0.10opt}$= 28 kW/(kg/s) for t_{a2} = 10°C reflecting the maximum rate ∑CDH/q_0 of summarized cooling degree hour ∑CDH number increment.

Meanwhile the typical methods of optimal cooling capacity calculation, based on the maximum current values of cooling degree hour CDH numbers, require the approximation of fluctuated values of cumulative current CDH numbers within a wide range of extremely uncertain values q_0 with deviations of about 20% (Figure 5).

In order to define a precise rational cooling capacity $q_{0.rat}$ excluding overestimation and reach practically maximum annual cooling degree hour numbers ∑CDH simultaneously a supplementary stage has been added to define the second maximum of the summerized cooling degree hour increment rate as (∑CDH– $\sum CDH_{opt}$)/$q_{0.15}$ in the range of $\sum CDH_{15}$ above the value $\sum CDH_{15opt}$ = 20,000°C•h corresponding to optimum cooling capacity $q_{0.15opt}$=18 kW/(kg/s) for t_{a2} = 15°C, accordingly, beyond $\sum CDH_{10opt}$ = 40,000°C•h and $q_{0.10opt}$= 28 kW/(kg/s) for cooling to 10°C (Figure 6).

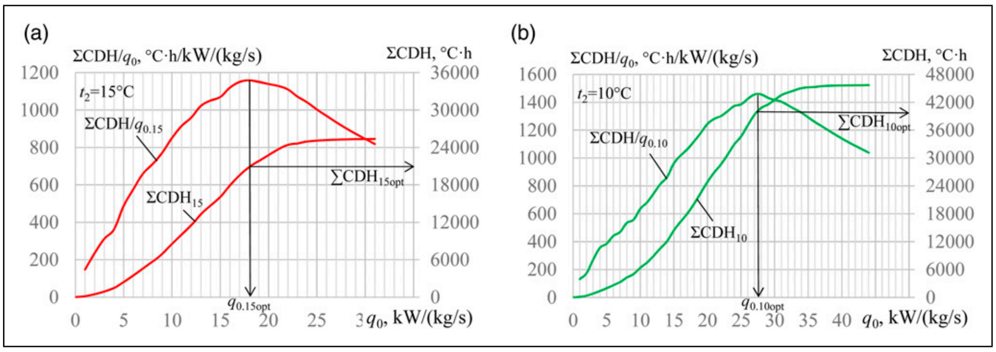

Figure 4. Annual summarized cooling potential $\sum$CDH and relative increment of summarized cooling potential $\sum CDH/q_0$ against specific cooling capacity q_0 for ambient air cooling: (a) – t_{a2} = 15°C; (b) – t_{a2} = 10°C; $q_{0.opt}$ and $\sum CDH_{opt}$ – optimal values.

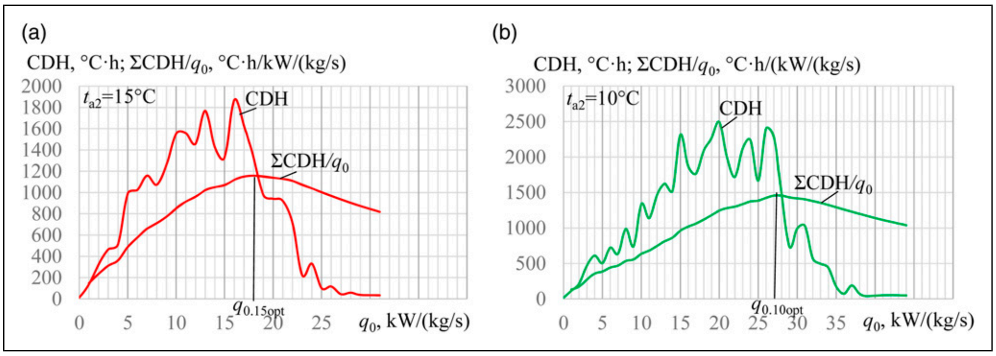

Figure 5. Cumulative current CDH numbers and relative increment of annual cooling potential $\sum CDH/q_0$ against specific cooling capacity q_0 for ambient air cooling: (a) – t_{a2} = 15°C; (b) – t_{a2} = 10°C; $q_{0.opt}$ and $\sum CDH_{opt}$ – optimal values.

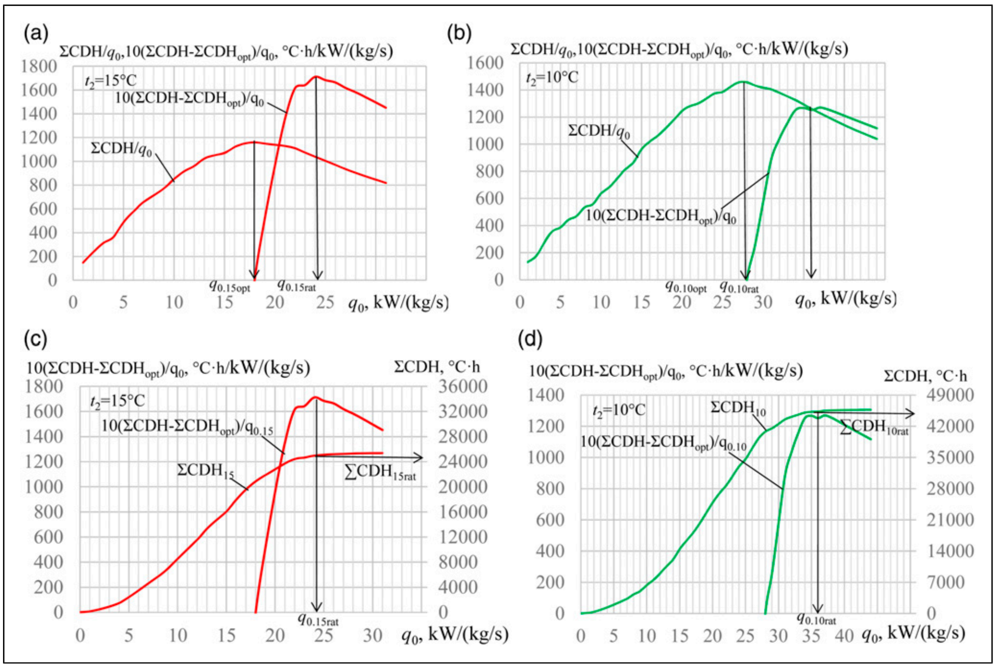

Figure 6. Relative increments of annual cooling potential $\sum CDH/q_0$ and $(\sum CDH- \sum CDH_{opt})/q_0$, summarized annual cooling potential $\sum$CDH against specific cooling capacity q_0 for ambient air cooling: (a) and (c) – t_{a2} = 15°C; (b) and (d) – t_{a2} = 10°C; $q_{0.opt}$ and $\sum CDH_{opt}$ – optimal values; $q_{0.rat}$– rational values.

As Figures 6(c) and (d) show, the third stage of developed methodology enables to define the proper rational cooling capacities $q_{0.rat}$ according to the second local maximum of relative summarized cooling degree hour increment as $(\sum CDH- \sum CDH_{opt})/q_0$ over the range of $\sum$CDH above the optimal value $\sum CDH_{opt}$ corresponding to optimum cooling capacity $q_{0.opt}$, calculated at the second stage (Figures 6(a) and (b)).

The rational cooling capacities $q_{0.rat}$ determined proceeding from the annual cooling degree hour $\sum$CDH for

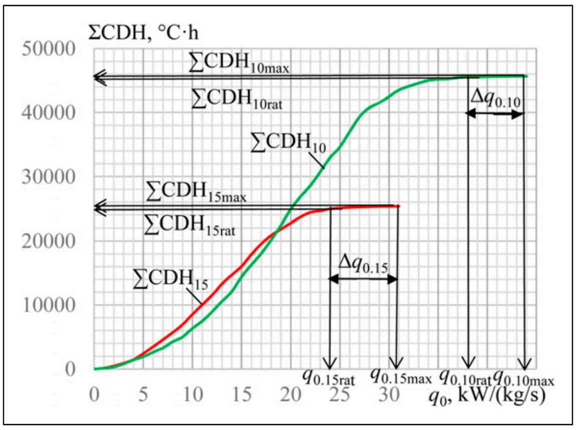

Figure 7. Annual ∑CDH numbers of ambient air cooling to 10°C and 15°C versus specific cooling capacity q_0: $q_{0.rat}$ and ∑CDH$_{rat}$ – rational values; $q_{0.max}$ and ∑CDH$_{max}$ – maximum values; $\Delta q_0 = q_{0.max} - q_{0.rat}$ – reduction in design cooling capacity.

ambient air cooling to 10°C and 15°C versus specific cooling capacity q_0 are presented in Figure 7.

As Figures 6(c) and 7 shows, the second maximum of the summarized cooling potential increment rate (∑CDH–∑CDH$_{opt}$)/$q_{0.15}$ for 15°C takes place at the rational cooling capacity $q_{0.15rat}$= 24 kW/(kg/s) reduced by $\Delta q_{0.15}$ = $q_{0.15max} - q_{0.15rat}$ against to its maximum $q_{0.15max}$ = 31 kW/(kg/s). Thus, the annual cooling potential ∑CDH$_{15rat}$ = 24,500°C•h is very closed to its maximum value ∑CDH$_{15max}$ =25,000°C•h and reached at rational value $q_{0.15rat}$= 24 kW/(kg/s) less than its overestimated value $q_{0.15max}$ = 31 kW/(kg/s) more than 20%.

Accordingly, for air cooling to 10°C the maximum rate of annual cooling potential increment (∑CDH–∑CDH$_{opt}$)/$q_{0.10}$ occurs at the rational value $q_{0.10rat}$=37 kW/(kg/s) associated with summarized annual potential ∑CDH$_{10rat}$ = 45,500°C•h practically equal maximum value of cooling degree hour ∑CDH$_{10max}$ =46,000°C•h. Meanwhile it is reached at a cooling capacity $q_{0.10rat}$ more than 15% lower compared to its overestimated value $q_{0.10max}$ = 44 kW/(kg/s) (Figures 6(d) and 7).

Graphs in Figures 4, 5, 6 and7 enable to match cooling duties at minimum sizes of intake air cooling system due to running at the optimal cooling capacity $q_{0.opt}$ (Figure 4) or to cover practically maximum annual cooling potential without noticeable oversizing due to operating at rational value $q_{0.rat}$ (Figure 7).

Conclusion

The advanced method to design any intake air cooling system (IACS) has been developed to off set actual cooling needs at minimum sizes when operating at optimal cooling capacity associated with maximum rate of summarized annual cooling degree hour increment or to peak practically maximum annual cooling needs when running at a rational cooling capacity.

The annual cooling degree hour ∑CDH number, calculated by summing the current cooling degree-hour CDH values, is accepted as a primary criterion for defining a design cooling capacity of IACS in contrast to the widespread practice of its application only for estimation of the effect due to sucked air cooling in combustion engines or air conditioning system.

A general novelty of the proposed methodology of IACS designing consists in modifying the well known method of estimating the effect due to sucked air cooling by annual cooling degree-hour number ∑CDH as primary criterion. The latter is modified by applying its relative value ∑CDH/q_0 as indicator for determining a design thermal load and cooling capacity q_0 accordingly, that enables to minimize chiller and IACS sizes and achieve practically maximum output due to cooling.

A new approach to consider the current fluctuations of CDH by the rate of the summarized values increment as ratio ∑CDH/q_0 enables to avoid inevitable inaccuracy caused by using the current values of CDH, fluctuated within a range more than 20%, or by approximation of yearly current values of CDH.

Due to rational designing, the annual cooling degree hour number ∑CDH and corresponding effect closed to their maximum are reached at a design cooling capacity less by 15 to 20% than its value selected according to conventional designing practice aimed to cover current peak demands.

A design cooling capacity of IACS, that provides a maximum rate of annual cooling degree hour number ∑CDH increment as ratio (∑CDH/q_0)$_{max}$ and minimum sizes of the system accordingly, is considered as the optimal value $q_{0.opt}$ for designing of IACS with thermal energy storage (TES), desired for accumulating the excessive cooling energy during lowered thermal loads to cover peak loads and to provide maximum annual cooling degree hour number ∑CDH and corresponding effect due to air cooling.

The use of proposed novel simple, easy for understanding and quite representative method, based on annular cooling degree hours ∑CDH, at the same time enables to define a precise design cooling capacity to avoid IACS and chiller oversizing.

Declaration of conflicting interests

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Appendix

Nomenclature and Units

CDH	cooling degree hour K•h
IACS	intake ambient air cooling system

Symbols and units

B	absolute fuel reduction, g, kg, t
b_e	specific fuel consumption g/kWh
c_a	specific heat kJ/(kg·K)
G_a	air mass flow rate kg/s
P_e	power kW
Q_0	overall (total) cooling capacity kW
q_0	specific cooling capacity kW/(kg/s) or kJ/kg
t	temperature °C
ξ	specific heat ratio of latent and sensible heat of air to its sensible heat
τ	time interval h
φ	relative humidity %
Δb_e	specific fuel consumption redudction g/kWh
Δt	temperature depression K, °C

Subscripts

a	air, ambient
a2	set value
max	maximum
opt	optimum
rat	rational