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Calculation procedures for free and renewable cooling technologies in non-residential buildings

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Dipl.-Ing. Heiko Schiller

Dipl.-Ing. Ronny Mai

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Goal of the research project

With the German Energy Saving Regulation (EnEv) of 2007, the cooling of non-residential buildings became, for the first time in Germany, the subject matter of energy-utilisation financial accounting in the context of the public-law verification procedure. The respective calculation procedure for cooling energy demand furnishes the DIN V 18599 standards (Version 02/2007) taken into consideration by the EnEv 2007, sections 2, 3 and 7 in particular. On the basis of the diversity of facility technologies available for cooling and air-conditioning, the calculation procedure to date in the area of cooling represents/indicates ostensibly standard technologies with conventional facility technology. This procedural objective offers the basis for a continuation of calculation methods in reference to energy-efficient technologies and the use of renewable energy sources. For these technologies, primarily calculation algorithms are being developed which are orientated to the procedure of utilisation financial accounting according to DIN V 18599. Moreover, on the basis of previously-used calculation procedures, new specific values for alternative cooling concepts are being ascertained.

In the focal point of the research project, we find the topic “free cooling” and the respective reduction of demand for conventional facility technology. In this regard, the facility-independent strategies of window ventilation as well as the facility/technological usable possibilities for free cooling through application of water re-cooling towers and free cooling registers are taken into consideration. Moreover, further alternative cooling methods are taken into consideration such as: evaporative cooling, dessicative dehumidification, the use of geothermal energy sources, and novel controlling strategies for conventional cold generators (frequency regulation), which can also make considerable contributions for reduction of primary energy demand. For a comprehensive assessment of energy flow between production and transference, assessment procedures for cold storage and multiple-producer facilities are being evaluated. In the final results, the research objective provides specific values and algorithms for energetic evaluation of alternative cooling technologies, particularly for non-residential buildings.

Execution of the research project

On the basis of the specific values procedure acc. to DIN V 18599 (issue 02/2007) used in the field of room ventilation and air conditioning, an extension of the calculation algorithms and specific values takes place. In the process, the basic interconnections of calculation procedures are retained in order to enable a non-problematic integration of results. All evaluations are based, in principle, upon a parameter study on the basis of complex simulation calculations and take into consideration the operating behaviour of the plant systems, the thermal behaviour of the enclosure’s construction, the thermal comfort and the outdoor climate. In order to ascertain the performance parameters of the cold generation, market research is carried out and validated by means of literature data and in-house measured values. The calculation of the energy specific values is carried out on the basis of a coupled building and plant simulation within an annual cycle.

Summary of the results

The research project provides specific values and algorithms regarding energy-based assessment of alternative energy efficient cooling technologies. The main focus of attention here is on free cooling and utilization of renewable energy sources. These specific values are compatible with assessment approaches in the normative national energy balance procedures (DIN V 18599), and thus applicable in the sense of a product-neutral energetic evaluation directly in the course of amending the EnEv.

Within the topic array **free cooling with window and night-time ventilation,** an evaluation was carried out regarding, first of all, how plausible the results are for the zone cooling demand with application of the monthly balance procedure. In this regard, a mathematical comparison between monthly balance procedure (DIN V 18599) and dynamic building simulation was accomplished. With the help of various model office rooms, it was possible to demonstrate that the monthly procedure, with identical basic conditions, can provide an extraordinarily good correlation, in part, in the annual demand values with the results from the dynamic simulation. Noticeable diversions appeared only within the monthly amounts, which were for the most part compensated for in the annual result.

Conversely, the standardised utilisation basic conditions according to DIN V 18599 – 10, lead in part to an under-evaluation of the cooling demand, since the internal gains of heat were set too low and, on the other hand, the duration and volume of window air change were set too high.

Window ventilation that goes beyond the hygienically necessary minimum can be referred to as “direct free cooling”. Buildings that offer this possibility give evidence of energy-related advantages compared to buildings with closed outside facades or buildings with large room depth. With the aid of variable calculations and comparative simulations, it was illustrated that the monthly balanceprocedure reacts very well to correspondingly adjusted ventilation basic conditions and can deliver plausible results in principle. Since, according to this author, previously excessive change of air forms the basis for the current norms, it is recommended that for now a conversion of increased window ventilation not be carried out.

The so-called summer-night-time ventilation can also contribute to a decrease of the cooling load, and thus also to useful energy demand for room cooling. At the moment the procedure EnEv / DIN V 18599 allows no possibility here for qualitative differentiation of buildings that allow this possibility.

As a basis for the physical modelling, the approach for verification of the summer heat protection according to DIN 4108 – 2 was adopted, according to which a change of air up to a double quantity can be implemented. In practice, it must be confirmed through controlling that no unacceptable undercooling of the rooms shall take place. Given these restrictions, the simulation calculations for the model rooms resulted in reductions of the cooling demand by a span of 6 to 17%, i.e. 3.3 to 7.5 kWh / (m² a).

For the empirical approach of implementing the effect of summer night ventilation into the monthly procedure, the following options were investigated:

- correction of the outdoor temperature
- increase in the window air change depending on the outdoor temperature
- increase in the window air change by a constant amount.

In view of the complexity of the unsteady heat storage procedures, it was unexpected that the simplest of the three approaches, namely the constant increase in the window air change, turned out to be the best correlation between monthly procedure and dynamic simulation. An optimally-best correlation for all of the simulated test rooms with office utilisation emerged when the window air change n_{win} was increased by a constant 50 %. For improved transferability to other utilisation profiles, the window air change should not be increased percentage-wise; rather, it should be raised by an absolute quantity. In the case at hand involving office utilisation, the factor 1.5 leads to an absolute increase in the mid-24-hour air change from 0.60 h^{-1} to 0.90 h^{-1}. The difference in the 24-hour mean value of 0.30 h^{-1} would, referenced to the daily non-utilisation time of 13 hours, correspond to an additional air change amounting to 0.55 h^{-1} and contains the influences of outdoor weather conditions and controlling. The equation (66) in DIN V 18599 – 2 would be replaced normatively as follows:

$$H_{V,win} = (n_{win} + \Delta n_{NL}) \cdot V \cdot c_{p,a} \cdot \rho_a$$

with Δn_{NL}: = 0 h^{-1};

if no possibility for ventilation with safety installations against break-in and driving rain are foreseen

= 0.3 h^{-1};

if an unrestricted possibility for free ventilation outside the main operational time exists

For **free cooling water re-cooling towers,** existing water re-cooling towers shall be used directly for cold supply in times of reduced thermal loads and thus less cooling loads. The refrigerating machine will not be put into operation (alternative operation) or it can be utilized for several re-cooling plants together with the free re-cooling plants (parallel operation). The partial coverage of load through free cooling brings an altered (mean) load case in this context of the refrigerating machine and has direct influence thereby upon the partial load factor PLV. Moreover, both the operating time $t_{RK,OP}$ and the utilisation degree $f_{R,RK}$ for the re-cooling plants change. With the help of simulation calculations, the influence of the free cooling for each mode of utilisation with consideration and variation of the essential influence values (construction weight, cold water temperature level, mode of operation - either parallel operation or alternative operation) for room cooling systems was investigated. In the process, the direct and respective shares of coverage of the free re-cooling, the operating times, and the degree of utilisation of the recoolers were ascertained with the assumption that no intermediate storage in cold storages or structural mass takes place. At the cold water temperature level of 10/15 °C (suitable for the transitional time period), the direct shares of coverage in this context are, in massive buildings particularly, often times only very low (< 5% for parallel operation) and non-verifiable for alternative operation. The highest share of coverage (max. 50%) can, as expected, be achieved with evaporative re-cooling installations in parallel operation at a server-room application. In the context of higher cold water temperatures (14/18°C), the shares of coverage tend to increase here slightly, however with very high cold water temperatures even the room cooling surfaces must be in respectively large dimensions. Lower cold water temperatures generate the opposite effect with a clearly decreasing share of coverage and should therefore be avoided through nominal value adjustment.

The **machine-integrated free cooling** is realized by the refrigerating machine manufacturers through various procedures. Most commonly, free cooling registers are operated in parallel operation with the condensers, which are cold water flooded and arranged in the return line. For the construction mode with integrated free cooling register, shares of coverage from the free cooling were also ascertained with simulation models. In this context, in addition to the changed partial load situation for the refrigerating machine, the altered air inlet temperature in the condenser was taken into consideration as well. In the final result, with the aid of the hourly ascertained annual performance rate of the free cooling on the one hand, and the refrigerating machine on the other hand – an annual performance rate of the overall technology $SEER_{FC}$ weighted with the annual cooling output was ascertained. By means of a comparison to the conventional operational case without free cooling, the free cooling factor f_{FC} ensues for the respective refrigerating machine; this factor illustrates the improvement in the performance rate through utilization of the free cooling. The free cooling factor f_{FC} was ascertained for typical air-cooled refrigerating units. It spans, dependent on usage, the range between 1.00 (for example, for massive building style, cold-water = 6/12°C) and 1.30 (server-room = 10/15°C) and shows the same tendency to dependencies such as free cooling systems with re-cooling plants (more considerable effect for lighter construction mode, higher cold water temperature, high cooling demand in the transitional period).

In the case of **indirect evaporative cooling** (aka: “adiabatic cooling”), we find a ventilation sub-process, in which the evaporation effect is used to cool the outdoor air. While the direct evaporative cooling (humidification of the inlet air) can be used in extremely dry climates, indirect evaporative cooling (humidification of the outlet air) can also be successfully applied in moderate climactic zones.

In order to evaluate the effect of indirect evaporative cooling, all variations of the installation with dry heat recovery with and without humidification of the outlet air were simulated. A total of 21 out of 46 variations from DIN V 18599 – 3 were affected. The potential for reduction of the annual cooling demand can amount to 10 up to 90 % with a wide statistical spread depending on the heat recovery rate, temperature and humidity requirements. The evaluation showed that the definition of a relative degradation factor f_{IEC} for the cooling demand offers practical advantages for the implementation of standardisation, since there exists no danger that the procedure could generate negative-demand-specific values through numerical inaccuracies. Based on the system of existing energy-specific values in DIN V 18599 – 3 Annex A, the degradation factors f_{IEC} were ascertained and tabulated. The conversion to differentiated inlet air target temperatures was accomplished through linear interpolation, for which the gradients $q_{\mathrm{IEC,u}}$ and $q_{\mathrm{IEC,o}}$ were equally calculated and tabulated. Further investigations involved various standardisation supplements. It was thus shown that the component operating time of the outlet air humidifier is almost identical to that of the air-cooler. As regards the cooler, the operating time can decrease due to indirect evaporative cooling. For this reason, correction factors were determined. The maximum air-cooler performance decreases as well due to the indirect evaporative cooling. If the outlet air temperature from the zone instead the outlet air temperature after the humidifier is applied, the existing formula set for the calculation of performance can be used. Corresponding instructions and supplements were formulated. By using load profiles with indirect evaporative cooling, the influence of the reduced machine coverage contribution on the partial load specific values for the refrigerating machine was investigated. The investigations showed that the diversions of the PLV values and the utilisation degree of the re-cooler did not exceed 5%.

DEC-Technology involves a fully climate process that can completely replace machine produced cold in many cases. The air temperature can be lowered directly and indirectly by water evaporation, when the outdoor air is pre-dried by a sorption procedure. The overall procedure requires heat at a lower temperature level as an absorption refrigerating machine, and is therefore also relevant for the implementation of renewable energy (key word: “solar air conditioning”).

In order to evaluate this process, a new simulation model had to be produced. The basis for it was the assessment of earlier investigations of the ILK regarding thermodynamic behaviour of sorption-rotors as well as their model-like programming. The sorption-supported air conditioning gives evidence of energy-based performance, in comparison to an analogue conventional air conditioning plant, as follows:

1. The cold energy demand is substituted by the implementation of regeneration heat at the sorption dryer. The description is generated by means of the degradation factor useful cold $f_{C,DEC}$, which can assume the amount zero at lower humidity demands and medium-level to high-level inlet air temperatures.

2. The description of the heat energy application is manifested analogously to the absorption refrigerating machine by the heat ratio ζ_{DEC}, which is defined as substituted useful cold for conventional cooling with consideration of the indirect evaporative cooling in relation to the implemented regeneration heat.

3. The energy demand for re-heating in the event of dehumidification decreases or is omitted. This effect was described by means of a degradation factor $f_{H,DEC}$.

It was waived the formulation of equations for calculation of the maximum component performance for the sorption-supported room air engineering units since the formula-related expenditure for the relatively seldom appeared technology would be too high. Due to the low variable quantity, maximum performances as volume flow related specific values were instead directly provided and tabulated. In an analogue system, the relative component operation times for the sorption-supported room air engineering units were determined per simulation and also provided as tabulation.

The primary goal, to implement the transformation of new technologies into the existing standards with low expenditure of time and effort, was reached. The expenditure regarding text descriptions, equations and tables was relatively low.

In the first instance the previously-used specific value procedure was extended for the energetic evaluation of the **room air engineering integrated refrigerating machines** in such a way that also for the air-cooled refrigerating machines a separate influence factor f2 became possible for the influence of variable re-cooling conditions. The factor f1 takes into consideration here the real machine-internal partial-load procedure with constant re-cooling conditions like for water-cooled systems. The factor f2 takes into consideration the thermodynamic coupling of the system with the outdoor air temperature as well as the outlet air temperature of the room air engineering integrated refrigerating machines. An essential impact on the efficiency of these refrigerating machines is the variable condensation temperature (outlet temperature after heat recovery) especially for room air engineering systems for which the cooling demand is supplied in connection with an indirect evaporative cooling with adiabatic outlet air humidification. The outlet air temperature after heat recovery and so the inlet air temperature in the outlet condenser of these room air engineering systems is lower compared to conventional room air engineering that results in an improvement of the producer efficiency (rising of partial-load factor f2). Therefore a differentiation of the partial-load specific values according to existing and non-existing indirect evaporative cooling is necessary for room air engineering integrated cooling technologies. Moreover, like for all technologies, the kind of room air engineering system and the building usage must be taken into consideration, since these parameters are decisive for the point in time of the cooling demand.

The partial-load factors PLV_{AV} of room air engineering integrated refrigerating machines at pure outlet air operation lie slightly under the values of pure outdoor air operation due to the outlet air temperatures that hovered midyear slightly above the mid-range outdoor air temperatures. In connection with a lesser performance rate due to the larger temperature difference at the condenser (ca. 20 K) caused by the installation situation, this also signifies a lower annual performance rate SEER (ca. -20%), and therefore a higher final energy demand for room air engineering integrated refrigerating machines compared to free installed conventional air-cooled refrigerating machines. The impact of the lower outlet temperatures with room air engineering systems with indirect evaporative cooling compensates this effect only partially. The partial-load factors f2 lie, for the absolute values, at 0.05 to 0.15 above those with pure outlet air operation without evaporation influence. The annual performance rate SEER of room air engineering integrated refrigerating machines is thereby reduced only by about -10% compared to free installed conventional air-cooled refrigerating machines.

Ascertainment of the specific values of **groundwater utilisation systems** is based on a thermodynamic and fluidic system assessment with application of various types of pumps and a validation of performed objects, particularly of the partial-load behaviour, with help from measured values. On the basis of defined input dimensions, nominal performance rates EER_{GW} of these technologies depending on the temperature spread as well as the probe depth were determined.

A numerical calculation model of an equivalent probe was used for the calculation of the efficiency of **geothermal probe facilities** which enables the determination of the probe outlet temperature and sampling capacity of simple U-probes depending on typical parameters like probe construction and diameter, ground-soil characteristics (heat conductivity) and probe depth. This model was extended for the calculation of commercially available double-U-probes in geothermal probe fields, which achieve a clearly higher sampling capacity at the same drill depth. The time and effort evaluation necessary for ascertainment of energy specific values, was accomplished on the basis of a thermodynamic and fluidic system evaluation with consideration of hydraulics of the water system and various kinds of pumps. The partial-load regulation of the groundwater utilisation units and geothermal probe facilities is defined by the mode of pump regulation. For the transformation into specific value procedure according to DIN V 18599, a differentiation is made between the conventional procedure for pump revolution control (constant pressure control) and unregulated pumps (throttle flow-control).

So the calculation results enable the specification of standard values for the efficiency of groundwater utilisation units EER_{GW} and geothermal probe facilities EER_{GS}. Partial-load specific values PLV_{AV} for the normative procedures were made available for the evaluation of energetic effects at typical operational behaviour of these facilities. Alternatively the separated detailed calculation of the expenditure (pump current demand) and of the benefit (sampling capacity of well, geothermal probe) is possible in the specific value procedure. The sampling capacity can be ascertained here project-specifically, depending on the parameters of probe style, probe depth and ground characteristics for geothermal probes and for groundwater utilisation units depending on allowed groundwater sampling quantity, well temperature of the groundwater and admissible discharge temperature. The required energy demand for this aim can be detailed calculated with the help of hydraulic calculation according to DIN V 18599-7 with consideration of the mean loading of the geothermal probe circuit.

Also **sorption refrigerating plants** of small capacity (<200 kW) and indirect-heated double-effect water/LiBr absorption refrigerating plants were included recently. The calculation of demand was accomplished analogously to normative specific value procedure with help of the specific values nominal heat rate ζ_N and mid-range partial-load factor PLV_{AV}. For this aim the manufacturing data of the manufacturer were evaluated and the commercially available nominal heat rates and internal pump energy demand values were deduced. Additionally, for all technologies a partial-load efficiency $PLV_{AV}=0.95$ and a utilisation factor of the re-cooling unit $f_{R,av}=0.65$ are pretended.

Furthermore **capacity controlled air- and water-cooled refrigerating units** with scroll, screw and turbo compressors were recently included in this normative calculation procedure. A lot of manufacturers were interviewed to ascertain the nominal performance rate and specific values of the PLV ratio. The submitted data were evaluated. In the result these specific values are now available for frequency controlled screw and turbo compressor systems (air- and water-cooled) and digitally controlled scroll compressor systems (air-cooled). The nominal capacity rates for the compression refrigeration technologies lies within the currently in DIN V 18599-7 used standard values of the nominal refrigerating capacity rate and can be used furthermore.

In reference to partial-load operation, there are now available partial-load factors that diverge from the previous procedures, not for 10% stages, but on the basis of the ESEER assessment in 25% stages. At the same time, a calculation procedure was developed with which the ESEER stage specific values ascertained under test-facility conditions at Eurovent can be recalculated into national partial-load specific values PLV. Utilisation of these product specific values is thus possible in the partial-load range.

An evaluation of the **cold storage** requires a differentiated observation of the planned operational mode and the respectively connected controlling concept for the storage technology, which, in addition to the dimensions and construction style, has an appreciable impact on the energy demand of the refrigerating machine. In order to illustrate these influence factors sufficiently exactly, in the future storage using rates and efficiency factors (storage factors) are to be considered depending on the operational mode of the storage.

The storage using rate $\eta c,s$ takes into consideration here the increase in the useful cold supply by means of storage losses and is significantly dependent upon the operational mode of the storage (rate time). The storage factor for sensitive (water-) storages $f_{sp,Wasser}$ takes into consideration the increase of the partial-load efficiency rate PLV of the refrigerating machine due to the lower partial-load frequency. During the storage loading operation, the EER (energy efficient ratio) is more or less constant. The storage factor of latent (ice) storages takes into consideration the increase of the partial-load efficiency rate PLV of the refrigerating machine by means of the lower partial-load frequency and the lower performance rate due to the lower evaporation temperature during storage loading operation. These specific values were calculated and tabularly prepared for the storage using concepts, weather prognosis regulation (optimal), storage unloading during the follow-up day (normal), peak load storage (bad) and capacity maintaining (redundancy).

The partial-load frequency of the individual unit changes at the application of several refrigerating plants (**multiple generation systems**). In order to illustrate this dependence in the normative-specific-value procedure as simply and as realisable as possible, a load-weighted partial-load factor for all individual units has been determined with the aid of predetermined scenarios for multiple generation systems. If one puts this in comparison with the partial-load factor of an individual generation system, one can calculate the change by the multiple generation system through a factor f_{MEZ}. Regarding the controlling of several systems, a difference must be made between sequence controlling and parallel operation. For sequence controlling, several cold generators of the same or different dimensions are operated in sequence, i.e. sequential circuit (master-slave and/or basic load / peak load). For parallel operation, several cold sources of the same or different dimensions are operated parallel and thus at the same time.

For both kinds of controlling, the relative change in the partial-load efficiency in reference to the individual unit was ascertained. The performance distribution of the sub-systems was varied according to realistic practice assumptions. For both sequential operation as well as parallel operation, in the result of the simulations, a strong dependence of the efficiency factor upon the partial-load controlling mode is noticeable. For the partial-load optimised systems (2), (8), (D) and (E), the performance distribution results in a reduction of the total efficiency. Conversely, for the energy-related bad partial-load controlling modes (3, (4), (C), (F) and (I), a strong improvement of the efficiency level is shown, since an improved capacity utilisation (higher partial-load stage) is achieved. For sequential controlling, a strong dependence upon the number of individual systems can be noticed. For parallel operation the factor f_{MEZ} increases, especially with rising performance differences between the smallest and largest refrigerating machine. Altogether the impact upon the efficiency of the complete system is however less-strongly pronounced compared to sequential controlling. Dependence upon the utilisation is low for all variants. The efficiency factor f_{MEZ} is therefore specified as system dependent in normative procedures.