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CRITICAL REVIEW OF WATER BASED RADIANT COOLING SYSTEM DESIGN METHODS

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SUMMARY

Interests in radiant cooling systems have increased in recent years. There is, however, no standardized method for radiant system design that is broadly accepted by the building industry. Through literature review, twelve surveys and eight interviews with leading practitioners, this paper summarizes the design methods documented in the guidelines, assesses the state of the industry, and identifies potential gaps and limitations in current design practice. The findings include: 1) design guidelines provide a wide range of approaches for cooling load calculation and system sizing; 2) most practitioners calculate cooling load for radiant systems the same way as for air systems, with only 23% of the respondents reported using dynamic simulation tools that have the capability to model radiant systems for cooling load estimation; 3) 46% of the respondents reported that steady state analysis methods/tools were used for radiant system sizing.

INTRODUCTION

Design guidelines have provided the principles and methods of designing radiant cooling systems, including load shifting, the use of operative temperature for comfort control, and cooling capacity estimation . However, there seems to be no obvious source of guidance on how to apply the design principles to applications and on the selection of tools for analysing performance and optimizing design. Anecdotal evidence suggests that a wide variety of methods are employed by radiant system designers. Practitioners would find benefit from a comprehensive review of existing design methods both documented in the guidelines and used by practitioners, which is the goal of this paper.

A radiant system is a sensible cooling and heating system that provides more than 50% of the total heat flux by thermal radiation. There are two primary types of water-based radiant systems: (1) suspended metal ceiling panels with copper tubing attached to the top surface (radiant ceiling panel, RCP); (2) prefabricated or installed-in-place systems consisting of embedded tubing in radiant layers (embedded surface system, ESS), and depending on pipe position and radiant layer constructions, ISO 11855 (Table 2 of part 2) further classifies the embedded system into seven types (A to G), including Type A-D which are those with radiant layers insulated from building structure, and tubing can be embedded in either surface thermal diffusion layer (screed or concrete) (Type A and C), or in insulation layer (Type B), or between insulation and surface diffusion layers (Type D), Type E which are those with plastic tubing (e.g., PEX) embedded in the structural slabs, often referred to as thermally activated building system (TABS), Type F, which are those with capillary tubes at the concrete surface, and Type G which features wooden construction with pipes in sub floor or under sub floor.

The process of designing a radiant system is similar to the design of an air system, including load analysis, system design and sizing, and whole building simulation for annual energy and thermal comfort performance. This paper will provide a comprehensive review of the analysis methods that are both documented in design guidelines and used in practice, and identify the gaps and limitations in current practice.

METHODOLOGIES

A literature review was first conducted, including current design guidelines and manuals developed by private radiant system design firms and manufacturers. This was followed up by interview/survey of practitioners and manufacturers about design methods. The survey consisted of four open-ended questions, investigating the adaptation of standard methods in the design community, identifying the range of approaches used in practice, adding observational information about design process, and understanding the tool selection criteria (see Table 1 for questions). Interviews were also conducted through email, face-to-face communication or a combination thereof to understand the industry practices. Interviewees included: 1) some of the survey respondents to confirm and clarify their answers and to follow-up with more detailed questions; 2) authors of publications that have described radiant system design approaches or specific projects; 3) leading radiant project designers. Besides the questions listed in Table 1 other questions were about the general design process, role of design parties, and their experiences with design tools.

Table 1: Survey questions

Q1: How do you calculate the cooling load of the spaces conditioned by a radiant cooling system? Which tools do you use?
Q2: How do you size the radiant slab system? For example, based on 24-hour total cooling load, peak cooling load, average cooling load during operating hours or others?
Q3: How do you estimate radiant cooling system capacity? Which tools do you use?
Q4: How do you handle cases with the presence of high solar heat gain (skylight, atria, perimeter zones, etc.)?

RESULTS

Space cooling load analysis methods

Table 2 provides a summary of cooling load analysis methods documented in the literature. Note that only original sources are listed, and the last column of the table provides cross-reference information. Currently, ASHRAE recommends two basic cooling load calculation procedures, the Heat Balance (HB) method and the Radiant Time Series (RTS) method. In addition to these two methods, there are other simplified methods (e.g., CLTD/CLF/SCL method, weighting factor method, etc.) that are widely used in modeling software for load prediction purposes. All these methods are developed with an underlying assumption that convective heat transfer by air is the only mechanism to remove heat from a zone. ISO 11855, Part 3 provides a step-by-step design process for radiant systems, but methods to obtain design cooling load were not included. Part 4 of the standard focuses on dimensioning of TABS, and suggests four sizing methods. The two major features of the methods are: 1) The design heat removal at the surface depends on operational strategy and load conditions, instead of a peak cooling load; 2) The design objective is to maintain the room operative temperature within a thermal comfort range, instead of maintaining a constant setpoint temperature. EN 15243 prescribes a sizing procedure. It implicitly acknowledges that cooling load is not a unique number but depends on the HVAC system type. It refers to EN 15255 for requirements on cooling load calculation method. In EN 15255, methods that are appropriate for radiant systems design that use operative temperature are classified as Class 4b. This implies that cooling load calculation methods for radiant systems should be properly distinguished from air systems. Load calculation methods specified in manufacturer's published manuals are mostly steady-state calculations. A design method, described in a manufacture design manual (Uponor 2013), discounts direct solar load from room cooling load assuming that solar flux that falls on a cooled surface can be removed instantaneously so that it is not going to become a room cooling load.

Radiant system design methods

The goal of designing a radiant system is to assure the system capacity to match the cooling load, which can be total or part of the design load. The process involves the determination of the following parameters: system types, specifications (tube diameter, spacing, floor finish, insulation, total tube length), and design operating conditions (surface temperature, flow rate, supply temperature, and pressure drop). Methods for estimating capacity of a combination of the parameters above are provided, and can be classified into calculation and testing methods (Table 3). Testing methods involve laboratory testing following a standardized procedure, and calculation methods involve using analytical or numerical methods. For radiant panel systems, only testing method is permitted. For embedded systems, both methods are allowed. However, the testing method is only described in EN 1264 and applies to floor heating system. If data is desired for cooling application or other surfaces, a conversion factor has to be applied. Regardless of method or system types, the representation of system capacity can take the same form as $q = K \Delta T$. Definitions of the parameters depends on system types.

Survey/Interview

The survey was deployed in August 2012 via email to twenty leading design practitioners, manufacturers, and top researchers who are experienced with radiant systems. In total, we received responses from twelve individuals. Eight interviews were also conducted.

Results from question 1 (see Figure 1) show that 31.8% of the respondents use tools that employed simplified ASHRAE load calculation methods (e.g. Radiant time series (RTS) or Transfer function methods), and 27.3% use steady state heat gain as cooling load. Even though 22.7% of the respondents reported using dynamic simulation tools that calculate space load based on heat balance methods and are capable of modeling radiant systems, those tools are generally perceived as being complicated, time consuming and high cost.

Table 2: Summary of load calculation method for radiant system sizing

Source	Description	Feature	Sizing	Load type	System type	Reference*
ASHRAE	Heat balance method	Dynamic	Peak	Air side	Not specified	1
	RTS, CLTD/CLF/SCL, weighting factor method	Dynamic	Peak	Air side		
ISO11855 P3	Describes split load between radiant and air system; no details for how to calculate load	NA	NA	NA	ESS	NA
ISO11855 P4 EN 15377	Rough sizing method: use daily energy gain to calculate required system capacity	Steady state	Daily energy gains	Surface	TABS	NA
	Sizing diagram: required capacity as a function of daily energy gain, orientation, operating hours, slab thermal resistance, etc.	Empirical	hydronic side cooling power	Hydronic		6
	Simplified model based on finite difference method	Dynamic	NA	NA		NA
	Dynamic building simulation program	Dynamic	NA	NA		NA
EN 15243	Provide load analysis process instead of detailed algorithm	NA	NA	NA	Not specified	2,3,5
EN 15255	Radiant system design methods are classified differently from methods for air systems; Use operative temperature as reference temperature for radiant system	NA	NA	Surface	Not specified	2,3,4,5
Uponor	Steady state heat gain method Direct solar load does not contribute to room load;	Steady state	Peak	Surface	ESS	NA
PRICE	Steady state heat gain method	Steady state	Peak	NA	RCP	NA

*Methods are referenced by various radiant system design manual or guidelines. 1: ASHRAE HVAC system and equipment (2012), chapter 6; 2: EN 1264 part 3 (2008); 3: ISO 11855 part 3. (2012); 4: EN 15377 (2007); 5: REHVA guidebook (2012); 6: Uponor, Radiant cooling design manual (2013).

Table 3: System capacity estimation and design methods in standards

Source	System type	Method type	Description		Notes
EN 14240	RCP	Testing	$q = K \cdot \Delta T^{n}$	Test chamber and load conditions represent interior zone conditions	1, 2
ASHRAE 138	RCP	Testing	$q = K \cdot \Delta T^{n}$	Test chamber and load conditions represent perimeter zone conditions	1, 2
EN 1264 part 2 clause 9	ESS (A-G)	Testing	$q = K \cdot \Delta T$	“Two plate” method to obtain the $K_{H,,Floor}$ for the case of floor heating, and convert it for cooling application and other surface type: $K = K_H(\Delta R_{\alpha,}, R_{\lambda,B}) = \frac{K_{H,floor}}{1 + \frac{\Delta R_{\alpha,} + R_{\lambda,B}}{R_{\lambda,B}}\left(\frac{K_{H,floor}}{K^{*}_{H,floor}} - 1\right)}$	1,3,4
ISO-11855 part 2 ; EN 1264 part 2 Clause 6 ; EN 15377	ESS (A-D)	Calculation	Simplified method using characteristic curves: $q = K \cdot \Delta T$	$K_{H, floor} = B (\prod_i \alpha_i,^{m})$ for floor heating	1,3,5
	ESS (A-D)			Conversion for cooling or other surfaces applications: $K = K_H(\Delta R_{\alpha,}, R_{\lambda,B}) = \frac{K_{H,floor}}{1 + \frac{\Delta R_{\alpha,} + R_{\lambda,B}}{R_{\lambda,B}}\left(\frac{K_{H,floor}}{K^{*}_{H,floor}} - 1\right)}$	1,3,4
	ESS (E, F)			$K = 1/ (R_w + R_r + R_x, + R_i)$	1,3,5
	ESS (G)			$K = 1/ (R_{HC} + R_i)$	1,3,5
	ESS (A-G)		Detailed	Finite Element (FE) or Finite Difference (FD) (see text description)	6
ASHRAE: Panel heating and cooling	RCP and ESS	Calculation	Steady state design graph based on characteristic panel thermal resistance, design parameters include design surface temperature, AUST (area-weighted indoor surface temperatures), cooling/heating output, water supply temperatures		NA

1. q is specific surface heat flux in W/m^2, and K is a lumped thermal resistance, n is a constant, and is equal to 1 for the embedded systems according to ISO 11855. Both K and n are to be determined by testing data or calculation method.
2. q is measured heat flux at hydronic level divided by panel area, ΔT is the temperature difference between mean water temperature and room operative temperature
3. $\Delta T = (T_V - T_R)/ln [(T_V - T_i)/ (T_R - T_i)]$, and T_V, T_R are the supply and temperature of cooling medium, T_i is design operative temperature
4. $\Delta R_{\alpha} = 1/\alpha - 1/10.8\ (m^2 K/W)$, and α is the total heat transfer coefficient depending on surface type (floor/celling/wall) and application (heating/cooling), $R_{\lambda,B}$ is the thermal resistance of surface covering, $K^{*}_{H, floor}$ is the resistance when $R_{\lambda,B} = 0.15$.
5. B is a system dependent coefficient, $\prod_i \alpha_i,^{m}$ is a power product linking the parameters of the floor construction with one another. R_w, R_r, R_x, R_i are thermal resistance between supply temperature and average temperature of the heating medium, between fluid and pipe wall, pipe wall, and between pipe outside wall temperature and average temperature of the conductive layer respectively.
6. The analysis may be used to calculate the heating and cooling capacity directly or the equivalent resistances.

For question 2 (see Figure 2), 71.4% of the respondents reported that peak cooling load was used for sizing radiant slab system. Two respondents also indicated that the capacity of radiant systems are too low compared to total cooling load, so the system will be sized to meet a constant base load, i.e., a rule of thumb maximum cooling capacity. Another two respondents mentioned they used steady-state average cooling load for sizing slab systems.

For question 3 (see Figure 3), besides commercially available dynamic simulation software, more than 46% of the respondents indicated that steady state analysis was conducted assisted by tools that are either based on ISO 11855 simplified method or finite element/difference methods or other algorithms. Respondents who reported using methods based on ISO 11855 are mostly manufacturers.

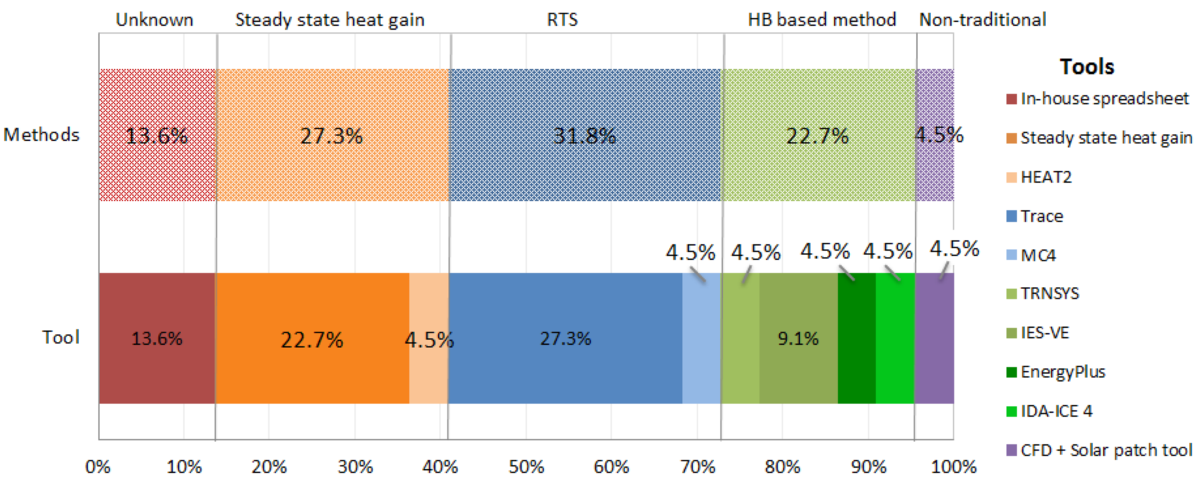

Figure 1: Results for question 1: Tools used for cooling load calculation (N = 22)

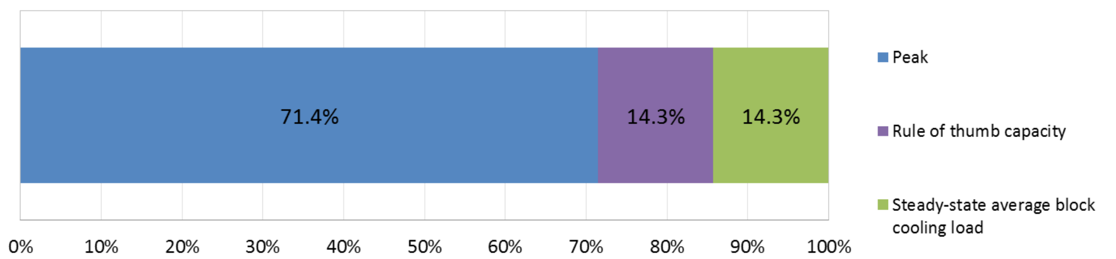

Figure 2: Results for question 2: Cooling load used for sizing radiant slab system (N=14)

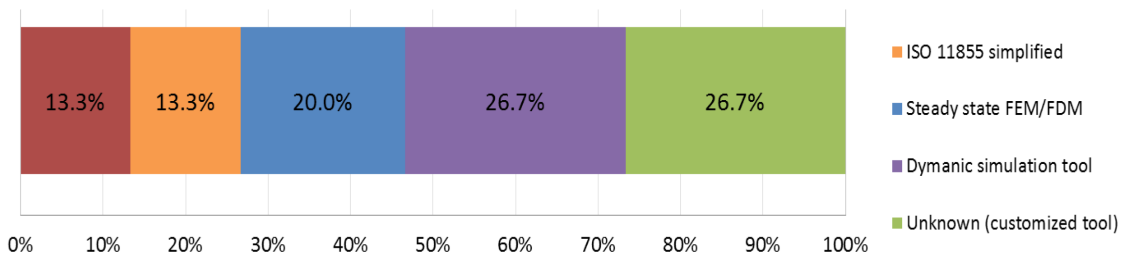

Figure 3: Results for question 3: Tools/methods used for designing radiant system (N = 15)

When practitioners were asked about designing for cases with solar load (question 4), the responses (10 in total) include: 1) always eliminate solar load (20%); 2) conservatively size the system as if there is no solar effect (20%); 3) size the system using a cooling capacity 1.25 – 2 times higher than normal cases (40%); 4) find sub-consultant (10%); 5) use finite element tools to take into account the impact of solar (10%).

DISCUSSIONS

For cooling load analysis, North American standards typically assume that a universal method can be used for any heating, ventilating and air conditioning (HVAC) system, while European or ISO standards, without suggesting detailed calculation algorithm, imply that methods may depend on system types, operational strategies, and controlled temperature. Most practitioners calculate cooling load for radiant systems the same way as for air systems. Compared to air systems, the chilled surface is able to instantaneously remove radiant heat from any external (solar) or internal heat source, as well as interior surface (almost all will be warmer than the active surface), within its line-of-sight view. Researches based on laboratory experiments and EnergyPlus simulation have shown that the cooling load profile and its peak value for a radiant system are different from those for an overhead mixing system , and the RTS methods may lead to incorrect results when used for radiant system (Bauman F et al.2013). Thus, there is a need to improve the understanding among practitioners about the differences between the two systems and provide guidance on selection of load analysis and modeling tools. For thermally massive systems that are designed and controlled for load shifting purpose, sizing based on peak load is unlikely to provide proper system. Methods presented in ISO 11855 have incorporated the concept of load management. However, there is no study to verify its applicability.

For radiant system sizing, design methods suggested in the standards, as well as most tools used by designers, conduct steady-state analysis. In addition, radiant surface boundary conditions applied in these methods do not accurately represent real building situations. For example, when calculating surface heat transfer coefficients, only natural convection and longwave radiation between active surfaces and other surfaces are considered, and radiant exchange from internal and solar gains are ignored. However, research has shown that radiant system cooling capacity could be enhanced by 30% with the presence of air diffuser , or up to 100% when the actively cooled surface is illuminated by solar .. In addition, for evaluation of environmental conditions and annual energy performance of a radiant system, radiant system model needed to be integrated in conventional building energy simulation packages. However, whole building simulation tools that have the capability to model radiant systems, such as EnergyPlus or TRNSYS, are not commonly adopted for the purpose of system sizing or annual performance evaluation.

CONCLUSIONS

This study has highlighted a number of trends regarding radiant system cooling load analysis and design methods documented in design standards and used by practitioners. The findings were based on literature review of design guidelines, twelve surveys and eight interviews with leading practitioners. For cooling load analysis, North American standards typically assume that a universal method can be used for any HVAC system, while European or ISO standards, without suggesting detailed methods, imply that methods may depend on system types, operating hours, and temperature control strategies. In the design community, 31% of the respondents reported using tools that employed the RTS method when designing radiant systems and 27% considered steady state calculation of heat gain to be sufficient. For radiant system design and sizing, more than 46% of the respondents reported that steady state analysis was conducted assisted by tools that are either based on ISO 11855 simplified method or finite element methods. In general, dynamic simulation tools that support radiant system modeling are not often used at the stage of cooling load estimation and equipment sizing.

ACKNOWLEGMENT

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