Room-side and Plenum-side Cooling Prediction of Suspended Radiant Ceiling Panels

Jun Shinoda [a,*], *Ongun B.* Kazanci [a], *Shin-ichi* Tanabe [b], *Katsuaki* Hidari [c], *Hiroki* Watanabe [c], *Yoshimi* Takahashi [c]

[a] International Centre for Indoor Environment and Energy, Department of Environmental and Resource Engineering, Technical University of Denmark, Koppels Allé, Building 402, 2800 Kgs. Lyngby, Denmark (* junshi@dtu.dk).

[b] Department of Architecture, Waseda University, 3-4-1 Okubo, Shinjuku-ku, Tokyo, 169-8555, Japan.

[c] Takenaka Corporation, 1-1-1 Shinsuna, Koto-ku, Tokyo, 136-0075, Japan.

Abstract. Hydronic radiant ceiling panels use a chilled surface to cool a room, and their cooling capacity is normally measured in a certified test chamber. However, current measurement standards calculate the cooling capacity of a panel based on the heat carried by the circulating water, which is the sum of the heat extraction from the room and plenum. Thus, sizing the radiant system based on the cooling capacity of the panels may result in an undersized system. In this study, a series of test chamber measurements and field measurements were conducted to quantify and empirically predict the proportion of the heat extracted from the room-side to the total heat extracted by the radiant panel. The cooling capacity of suspended radiant ceiling panels was first measured in a certified test chamber, with the temperature difference between the room and plenum as the main parameter. Within the tested temperature range (plenum temperature of 24 – 28 °C, room temperature of 26 °C), the heat extracted from the room side was 77 – 92 % when the panels were insulated and decreased to 46 – 71% when they were not insulated. A simplified, empirical approach for estimating the heat extraction at both sides of the panel was proposed based on the obtained results. A field measurement was then conducted to examine the validity of the proposed methodology. Measurements were conducted in an office building located in Japan, which was equipped with radiant ceiling panels of the same type as the ones tested in the chamber measurements. Heat flux sensors were placed at both the room and plenum sides of a single radiant panel to obtain the proportion of heat extraction from the room-side. The measured room and plenum temperatures were used as input for the prediction of the room-side heat extraction ratio, and the average error of the predicted heat flux was 6%, confirming the validity of the proposed methodology.

Keywords. Radiant Ceiling Panel, Chilled Ceiling, Cooling Capacity, Radiant Cooling, Plenum
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1. Introduction

Prefabricated radiant ceiling panels are a common form of radiant heating and cooling systems. As opposed to embedded systems, which often requires on-site construction and therefore a numerical estimation of its cooling performance, prefabricated panels can have their cooling capacity measured in a test chamber. However, current measurement standards such as EN 14240 [1] calculate the cooling capacity based on the heat carried by the circulating water, which is the total heat extracted from the room and plenum. Field measurements conducted by Li et al. [2] showed that about 30 – 40% of the heat extraction by the water circuit of suspended radiant ceiling panels was from the plenum. Ito et al. [3] conducted tracer gas measurements to quantify the air exchange between the room and plenum, and developed a numerical model for cooling capacity predictions. Further simulations with the developed model was performed by Ojima et al. [4], and it was concluded that sizing a radiant panel system based on the manufacturer-stated cooling capacity may result in an under sizing of the system.

2. Methodology

The purpose of the current study was to present possible improvements to the cooling capacity measurement procedure of suspended radiant ceiling panels. Test chamber measurements were conducted following the same setup and procedure as stated in the standards [1, 5] but with different plenum temperatures to quantify its effect on the cooling capacity and proportion of heat extraction from the room and plenum. A simple, empirical model to predict the room-side heat extraction was then developed. Finally, the proposed model was validated with dataset obtained in the field.

2.1 Chamber measurements

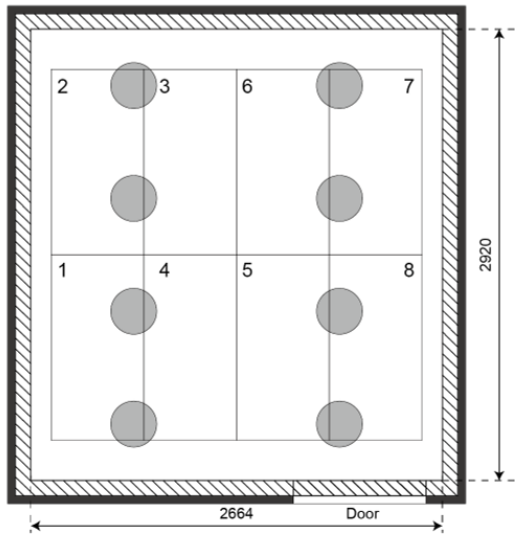
The radiant panel selected for this study was composed of capillary pipes. Table 1 lists the physical properties of the panels. The cooling capacity was measured according to the ARCH 2017 CHTRS standard [5], a Japanese standard derived from the EN14240 [1]. The nominal cooling capacity is the measured heat extraction from the panel circuit with 8 K difference between the mean water temperature and the room temperature. The panel comes with an optional insulation layer, and the nominal cooling capacity is slightly lower when the panel is insulated.

Table 1 – Physical properties of the measured panels.

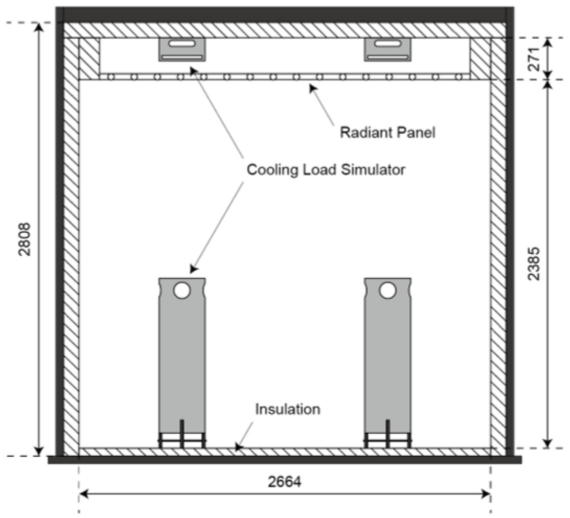
Properties	Units	Description
Dimensions	mm	584 × 1184 × 8
Nominal Cooling capacity	W/m²	61 (non-insulated); 58 (insulated)
Panel Material	-	Aluminium
Pipe material	-	Polypropylene
Inner/Outer Pipe Diameter	mm	2.3 / 3.4
Insulation (optional)	-	32 kg/m³ glass wool, 40 mm, 0.036 W/(m·K)

Fig. 1 shows the dimensions of the chamber. Eight suspended radiant ceiling panels were installed as one circuit, without any intentional gaps. The remaining ceiling surface was covered with insulation. The numbers on the panels denote their order in the panel circuit. The chamber had dimensions of 2.664 m × 2.920 m × 2.385 m. The chamber complied with the EN14240 and ARCH 2017 CHTRS standards [1, 5], and the measurement procedures followed those specified in these standards, except for the cooling loads that were added to the plenum for the purpose of the study.

The room reference temperature was measured by a black globe thermometer positioned in the center of the room at a height of 1.1 m. The plenum reference temperature was substituted by the average of the air temperature and uncooled/surrounding surface temperatures (area-weighted). Surface and air temperatures were measured with thermocouples with accuracies of ±0.5 K. All the sensors were calibrated against a Pt100 temperature sensor with an expanded uncertainty of 0.02 K.



(a) Plan



(b) Section

Fig. 1 – Dimensions of the test chamber (units: mm).

For both the room and the plenum, eight cooling load simulators were each installed to enable temperature control of both spaces. For each measurement case, the room and plenum temperatures were controlled by adjusting the electrical input to the cooling load simulators and the supply water temperature to the panel circuit. The supply water flow rate was fixed to 3.33 L/min. The surrounding wall and floor temperatures were maintained at a temperature as close as possible to the room temperature by the hydronic pipes embedded behind each surface. All the surfaces except for the radiant panels were covered with insulation at the inner side of the chamber.

Table 2 lists the measurement cases. For each case, the room reference temperature was maintained at 25.7 ± 0.1 °C. The temperature differences between the room reference and mean water temperature of

6, 8, and 10 K were tested. In addition, for each temperature difference, the plenum temperature was adjusted to approximately 24, 26, and 28 °C (corresponding to ± 2 K from the room reference temperature). Nine tests were conducted for non-insulated panels and three for the insulated panels. Each measurement case was conducted for 15 min with a logging interval of 30 s under steady state conditions. Electrical inputs to the cooling load simulators of the room and plenum were assumed to be the heat extracted from each space. The cooling capacity of the panels and the extracted heat from each space were compared and used for analysis.

Table 2 – Measurement cases.

Case name	Room reference temp. [° C]	Plenum reference temp. [° C]	Room reference – mean water temp. [° C]
Non-insulated Panels			
N_6_-2	25.7	23.8	6.0
N_6_0	25.8	25.6	5.9
N_6_+2	25.8	27.5	5.9
N_8_-2	25.7	23.7	7.8
N_8_0	25.7	25.7	7.7
N_8_+2	25.7	27.5	7.5
N_10_-2	25.7	23.5	9.5
N_10_0	25.7	25.5	9.4
N_10_+2	25.7	27.6	9.2
Insulated Panels			
I_8_-2	25.6	23.8	7.9
I_8_0	25.8	26.1	7.9
I_8_+2	25.7	27.9	7.8

2.2 Model Development

ISO 11855-2 [6] provides an equation to calculate the downward heat loss of an embedded floor heating system. In this study, the same equation was used for the plenum-side heat extraction for the radiant ceiling panels, as shown in equation (1).

$$q_p = \frac{U_{w,p}}{U_{w,r}} q_r + U_{w,p} \cdot (t_p - t_r) \qquad (1)$$

Where:

- q_p : plenum-side heat flux (W/m²)
- q_r : room-side heat flux (W/m²)
- t_p : plenum reference temperature (°C)
- t_r : room reference temperature (°C)
- $U_{w,p}$: heat transfer coefficient between water and plenum (W/(m² · K))
- $U_{w,r}$: heat transfer coefficient between water and room (W/(m² · K))

If the two spaces have the same temperature ($t_p = t_r$), the equation could be further simplified in the form of equation (2), and the ratio of the room-side heat flux to the total heat extraction can be expressed as equation (3).

$$q_p = \frac{U_{w,p}}{U_{w,r}} q_r \qquad (2)$$

$$\frac{q_r}{q_r + q_p} = \frac{\Delta t_{w,r}}{\Delta t_{w,r} + \frac{U_{w,p}}{U_{w,r}} \cdot \Delta t_{w,p}} \qquad (3)$$

Where:

- $\Delta t_{w,p}$: difference between mean water and plenum temperatures (K)
- $\Delta t_{w,r}$: difference between mean water and room temperatures (K)

In this study, the heat transfer coefficients ($U_{w,p}$, $U_{w,r}$) were substituted with an empirically obtained coefficient that is dependent on the temperature difference between the room and plenum so that equations (2, 3) could be used even when the room and plenum temperatures are not the same ($t_p \neq t_r$). A linear regression of the results obtained from the test chamber measurements were used to obtain the empirical heat transfer coefficients.

2.3 Field measurements

To validate the empirical prediction method described in section 2.2, dataset obtained from a field measurement was used. The case study building was a newly constructed office in the Greater Tokyo Area of Japan. The radiant panels installed in the building was the same type (product) as those tested in the test chamber measurements. The radiant ceiling panels covered 58% of the ceiling surface. The ceiling height was 2.8 m, and the plenum height was 1.08 m.

Fig. 2 shows the typical floor plan of the building. The office floor had dimensions of 56.4 × 56.4 m, and the office area (open plan layout) was positioned along the north, west, and south sides. The remaining area are the building core and meeting rooms.

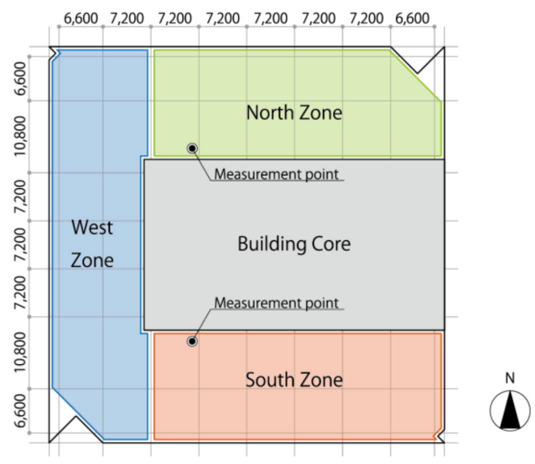


Fig. 2 – Floor plan of case stud building (units: mm).

Field measurements were conducted continuously in the summer of 2020, between 18 – 25th of August, in the north and south zones. In each zone, heat flux sensors and thermocouples were placed on the room- and plenum-sides of a single panel, and they were logged in 1 min intervals. The air and globe temperatures of the plenum was measured above the selected panels with a 5 min logging interval. The room temperature was obtained from the Building Management System (BMS), which was logging at a 1 min interval.

The building was at its first year of operation, and therefore in the phase of tuning the operation and control of the systems. During the measurement period, the room temperature setpoint was adjusted between 24.5 and 25.5 °C, which allowed the measurements to be conducted under different temperature conditions.

3. Results and Discussion

3.1 Room and plenum cooling loads in the test chamber

Fig. 3 shows the cooling load in the room and plenum for the 12 measurement cases. The cooling load was divided by the installation area of the panels (5.76 m^2). The room-side load ratio was calculated by the ratio of the room-side load to the sum of the room and plenum loads. The results were grouped in sets of three cases, according to the difference between the mean water and room reference temperature (6, 8, 10 K) and insulation type (N: non-insulated, I: insulated). Within each group, the plenum temperatures were set to 2 K lower than room temperature, equivalent to room temperature, and 2 K higher than the room temperature (-2, 0, 2 K).

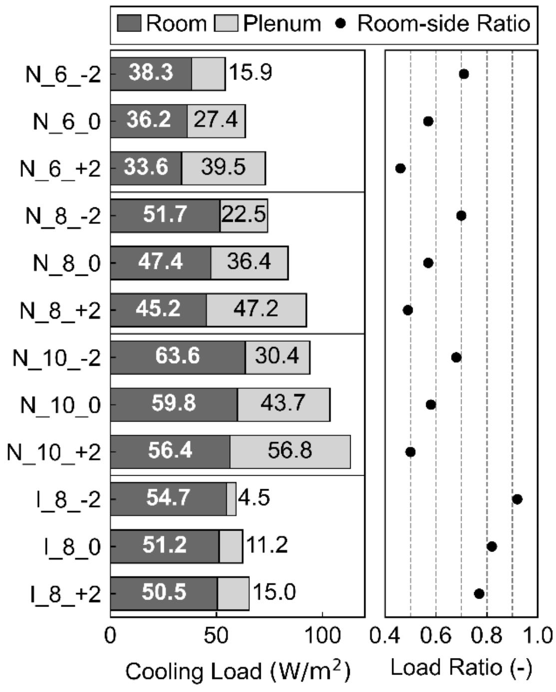


Fig. 3 – Cooling load in the room and plenum

The results show that the increase in plenum temperature increases the total cooling capacity (i.e., total heat extraction from the room and plenum) but decreases the proportion of the room-side heat extraction. When the plenum temperature was 2 K higher than the room temperature, about half of the cooling was from the plenum-side for non-insulated panels. Insulated panels were able to decrease the amount of cooling to the plenum, but the room-side ratio dropped to 0.77 when the plenum temperature was 2 K higher than the room temperature, which is non-negligible. In the observed scenarios, the room-side ratio of non-insulated panels ranged between 0.46 and 0.71, and the ratio of insulated panels ranged between 0.77 and 0.92.

3.2 Empirical adjustment of heat transfer coefficients

Fig. 4 shows the empirical heat transfer coefficient between the water and room/plenum in relation to the temperature difference between the two spaces. The heat transfer coefficient was calculated by dividing the loads in Fig. 3 by the mean water and room/plenum reference temperature differences. Note that these values are different from the actual HTC ($U_{w,p}$, $U_{w,r}$) in equations (2), (3). For both the insulated and non-insulated panels, the obtained coefficients showed a linear relationship with the temperature difference between the room and plenum. Therefore, the empirical heat transfer coefficients to be used in equation (3) can be calculated with equation (4).

$$U = X \cdot (t_p - t_r) + Y \tag{4}$$

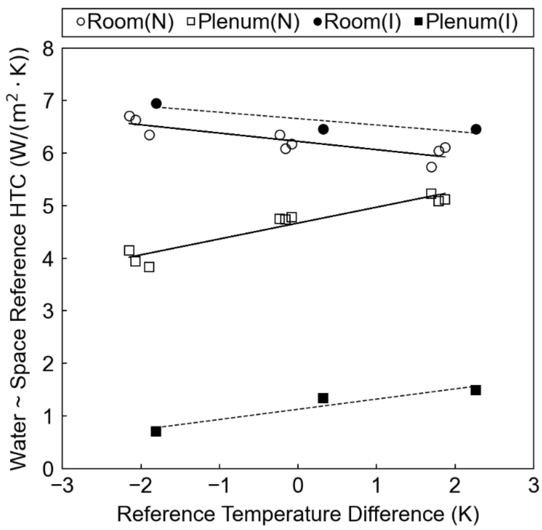


Fig. 4 – Empirical heat transfer coefficients (HTC: heat transfer coefficient, N: non-insulated panels, I: insulated panels)

The slope (X) and intercept (Y) for the non-insulated panels are listed in Table 3. The slope is negative for the room-side and positive for the plenum-side, as the cooling rate at the room-side will decrease, and increase at the plenum-side when the plenum temperature is higher than the room temperature. These empirical values are unique to each panel type, and therefore the same measurement procedures have to be followed to obtain corresponding values for each product.

Table 3 – Slope and intercept of heat transfer coefficient adjustment (non-insulated panels)

Constants	Corresponding Space	
	Room ($U_{w,r}$)	Plenum ($U_{w,p}$)
Slope (X)	-0.158	0.302
Intercept (Y)	6.224	4.669

3.3 Validation of prediction model in the field

The plenum globe and room temperature from the field measurement was used to predict the room-side heat extraction ratio of the panel, with equations (3) and (4), and the values in Table 3. The predicted value was compared against the ratio of the room-side heat flux to the sum of heat flux at both sides of the measured panel.

Fig. 5 shows the heat flux and room-side ratio of a representative day in the south zone. The symbol of the heat fluxes was reversed (positive: cooling, negative: heating). The heat fluxes are shown as a stacked value. The bypass signals of the panel circuits could not be obtained from the BMS, and thus the exact time in which cooling water was supplied to a specific panel could not be obtained. Therefore the ratio was assumed to be zero when the main pump of the panel circuits was turned off or when the ratio exceeded 1 (i.e., when one side was heating and the other was cooling).

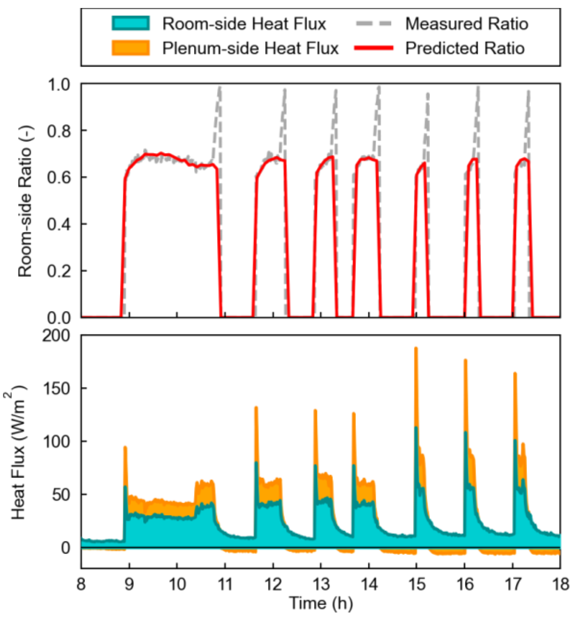


Fig. 5 – Heat flux and flux ratio of a representative day (South zone; Monday, 24. August 2020)

The results show that the room- and plenum-side heat flux varied at different times of the day, and with a different operation interval. This is mainly due to the variation of the supply water temperature to the panels in response to the tuning of the whole system operation. However, the room-side ratio was maintained at around 0.6 to 0.7, which was similar to those reported in previous studies [2]. The predicted room-side ratio and its time response was in good agreement with the measured ratio. The measured ratio deviated from the predicted value when the heat flux of the panel decreased, presumably when water supply was bypassed from the panel being measured.

Fig. 6 shows the comparison of the measured and predicted room-side heat flux ratio throughout the whole measurement period (but limited to occupied hours). As the results from Fig. 5 showed that the prediction model is applicable when there is water circulation to the panels, the plots were further filtered. Only the measurements that meet the criteria of a room-side heat flux higher than 22 W/m² and a plenum-side heat flux higher than 14 W/m² were considered to be instances when the panels were turned on. The criteria corresponds approximately to a 2 K temperature difference between the active surface and the reference temperature in the room/plenum [7].

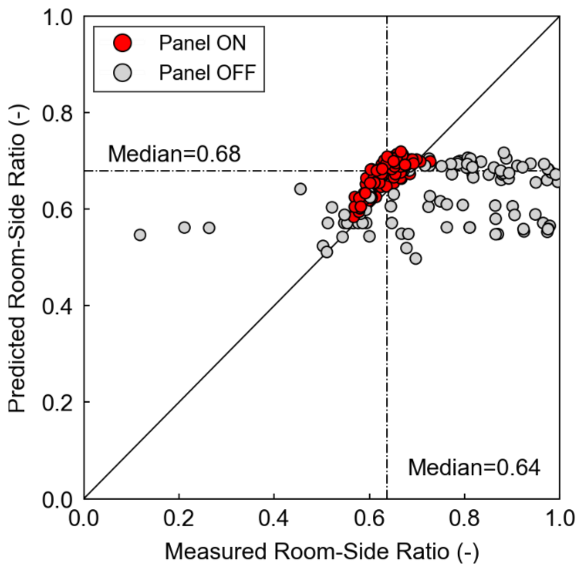


Fig. 6 – Measured and Predicted Room-side heat flux ratio (all measurement period)

The comparison of the measured and predicted ratio over the whole measurement period shows a good agreement between them. The difference between the measured and predicted ratio ranged from -0.02 to 0.08, with an average of 0.04. This corresponded to an average error of 6% (with a standard deviation of 3%) for the room-side heat flux. The validity of the proposed methodology was thus confirmed.

4. Overall Discussion

The results from the test chamber measurement showed that the plenum temperature has a considerable effect on the cooling capacity and proportion of the room-side cooling. It is highly recommended that radiant panels be insulated to prevent unnecessary cooling of the plenum. However, in the tested conditions for the insulated panels, when the plenum temperature was equal to or higher than the room temperature, about 20% of the cooling was dedicated to the plenum, which cannot be dismissed. Therefore, regardless of the panel insulation, cooling capacity measurements should be conducted with different temperature differences between the room and plenum. The calculation of the heat balance within the plenum is critical, especially for cases in which larger loads are to be expected in the plenum e.g., in a top floor where the ceiling slab is exposed to solar radiation, or when waste heat from lighting armatures may be present.

When evaluating a single zone of a building, cooling of the plenum would be an excess use of energy. In a multi-story building, a cooled plenum may provide additional cooling to the floor above, or provide cooling to the room with a time delay. Whether or not the cooling of the plenum would be beneficial for the entire cooling system would depend on multiple factors, such as building construction, control and operation. This would require further studies.

5. Conclusion

A series of test chamber measurements and field measurements were conducted to provide improvements to the cooling capacity measurement of suspended radiant ceiling panels. The conclusions were as follows.

- Test chamber measurements were conducted to quantify the effect of plenum temperature on the cooling capacity and the proportion of cooling to the room and plenum. With a plenum temperature 2 K lower to 2 K higher than the room temperature, heat extraction from the room-side was 46 – 71% for non-insulated panels and 77 – 92% for insulated panels.
- Based on the equation presented in ISO 11855-2 [6], an empirical equation to predict the room-side heat extraction ratio was developed. The necessary values for this calculation may be obtained by repeating the measurement procedure of this study.
- Data from field measurements were used to validate the developed model. The case study building had the same type of radiant panel as those tested in the test chamber measurements. Heat flux at both sides of a selected panel was compared against the predicted values. The model was able to predict the room-side heat flux with an average error of 6% when water was being supplied to the panels. The validity of the proposed methodology was thus confirmed.

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7. Data Access Statement

The datasets generated during and/or analyzed during the current study are not available because of a non-disclosure agreement but the authors will make every reasonable effort to publish them in near future.

8. References

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