Assessment of thermal comfort performance of membrane-assisted radiant cooling outdoors

Yan Liang[1,#], *Junran* Yang[1,#], *Ziwen* Zhong[1,2], *K.* Dharmasastha[1], and *Jian-Lei* Niu [1*]
[1] Department of Building Energy and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
[2] School of Mechanical and Electrical Engineering, Shenzhen Polytechnic University, Shenzhen, China
[#] These authors contribute equally to this work.

Abstract. Membrane-assisted radiant cooling panels provide the possibility of active cooling in outdoor environments by reducing convective heat transfer between the radiant surface and open air and mitigating the risk of condensation. A membrane-assisted radiant cooling panel system was constructed in an open space to perform thermal comfort investigations. There were 248 subjects participating in the thermal comfort investigation under three different panel surface temperatures. During the experiment, the subjects were asked about their feelings about thermal sensation. It was indicated that the thermal sensation vote (TSV) improvement percentage is higher in the transitional season compared to the hot season. The thermal comfort created by the cooling of the back trunk offsets the thermal discomfort on the front side of the body (e.g., face, head, chest, etc.) and, therefore, lowers the overall TSV even if the subject stands under the cooling spot with some degree of radiant asymmetry. This study would be helpful for future research on improving thermal comfort in outdoor environments.

1. Introduction

A comfortable outdoor thermal environment is conducive to people's daily life. Growing attention is being paid to creating sustainable, liveable, and resilient outdoor environments in cities due to the increasingly adverse impacts of climate change. Outdoor air is closely related to the atmosphere, and its air temperature, humidity, and flow rate do not create a comfortable space like indoor environments that utilize air conditioning and convection. Radiant cooling systems, on the other hand, create thermal comfort by absorbing body surface heat through radiant heat transfer [1]. However, in hot and humid areas, the convective heat exchange between the radiant panel and the ambient air has little cooling effect on the human body. It only causes a large degree of energy waste. Meanwhile, due to the high dew-point temperature of the atmosphere, condensation is a problem that needs to be solved urgently.

Fortunately, a series of recent studies, such as using selective short-wave radiation through the film to isolate the outdoor air and the cold radiation surface, thereby improving the cooling capacity of the radiant panel of the cooling capacity [2, 3] and anti-condensation ability. The concept that utilizes an infrared transparent membrane to isolate the radiant cooling surface and ambient air was first induced in 1963 by Morse [4]. This approach creates an air layer that generates a temperature difference between the cooling panel surface and the membrane, reducing the convection heat transfer and condensation risks at the radiant surfaces. The air-contact membrane temperature can be maintained above the dew point of the ambient air to avoid condensation [4]. Recently, Teitelbaum et al. [5] completed a pilot experimental study outdoors in Singapore, using 50μm LDPE film to assist radiant cooling, demonstrating that radiant cooling can provide thermal comfort in high air temperatures. It also obtained that the thermal sensation of the subjects was reported as 'satisfactory' 79% of the time. Moreover, in their research, devices could be installed free of condensation at a difference of 10 K between MRT and air temperature and with a water supply temperature below the dew point temperature. However, the structure in the Teitelbaum et al. study was a semi-enclosed space, which means that unavoidable outdoor factors such as wind and solar radiation were not considered. So, the thermal comfort of radiant cooling systems in real outdoor applications remains unclear. The objective of this study is to experimentally explore what outdoor thermal comfort can be improved for people staying outdoors by using a membrane-assisted radiant cooling system in hot and humid Hong Kong. The study's findings can help disclose how much comfort radiant cooling can provide for people, which would be for future applications of radiant cooling in outdoor environments.

*Corresponding author: jian-lei.niu@polyu.edu.hk

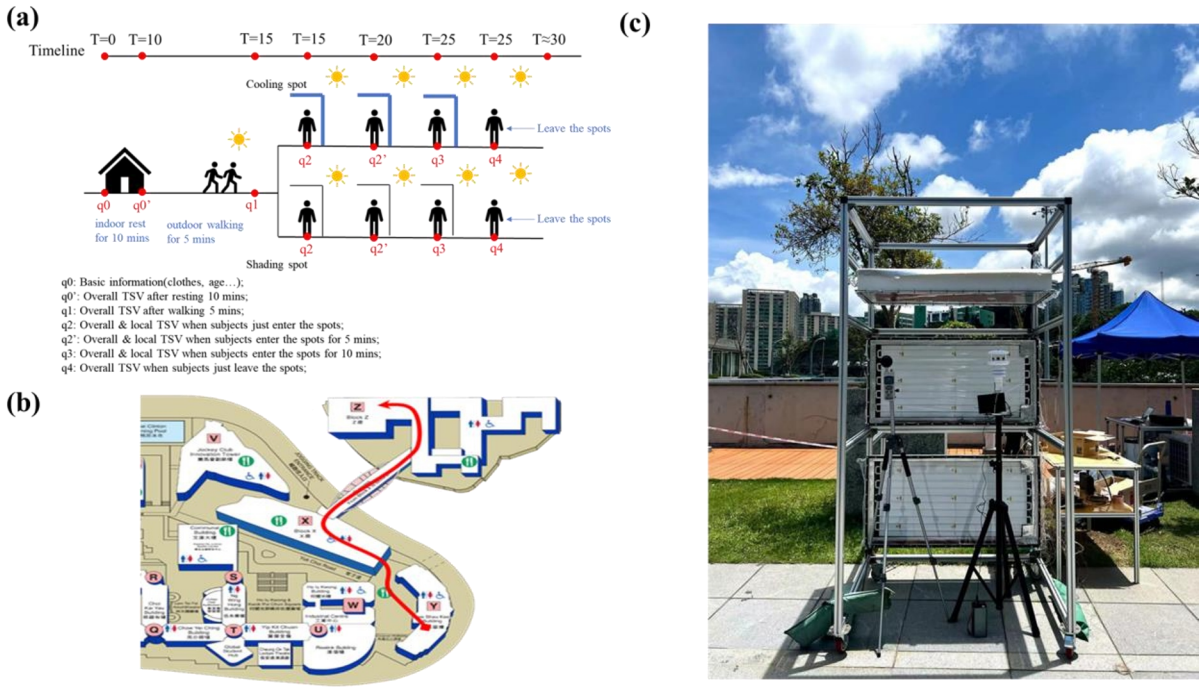

Fig. 1. Thermal comfort survey procedure. (a) Timeline and overview of the experimental process for the subject. (b) Route diagram for a 5-minute outdoor walk. (c) A cooling spot with three radiant cooling panels (shows a mini weather station and a black globe thermometer).

2. Method

2.1 Experiment facilities

Membrane-assisted radiant cooling panels were used to prevent condensation [5]. The membrane-assisted cooling panels were covered by a low-density polyethylene (LDPE) membrane. Silica gel desiccant is placed in the air layer between the cooling panel surface and the LDPE membrane to absorb the moisture in the air layer. Hence, the risk of condensation on the cooling panel surface can be reduced.

2.2 Experimental procedure

The procedural flow of thermal comfort survey is illustrated in Fig.1(a), displays the different questionnaire contents corresponding to each time. Spanning approximately 30 minutes, the experiment required human subjects to complete seven distinct questionnaires at varied times and locations, facilitating comprehensive data collection. For instance, at t=0, human subjects were seated indoors, completing the q0 questionnaire. This first questionnaire (q0) captured personal details (such as weight and height), clothing type, current mood, and instantaneous thermal comfort. Each questionnaire from q0' to q4 featured items on overall thermal sensation and comfort, current mood, and thermal preference. Additionally, questionnaires q2, q2', and q3 included questions on the local body part of the thermal sensation, and the human subjects were inquired about which body parts were directly exposed to sunlight. In each experimental group, two human subjects followed the same experimental procedure. However, their positions varied: one stood at a cooling spot offering both shade and cooling, while the other was positioned beneath a device providing only shade.

A total of 248 questionnaires were collected from people from the Mainland or Hong Kong who had lived in Hong Kong for more than 15 days. Half of them were obtained from participants in the cooling group, and the remaining half from those in the blank control group. The space where the cooling group is located is called the ‘cooling spot,’ while the blank control group is called the ‘shading spot.’ Human subjects in this study encompassed college students and university employees, ranging in age from 17 to 40. Human subjects were not required to adhere to any specific dress code during the survey. The gender distribution of the subject sample was relatively even, with 50.8% of males and 49.2% of females, while the BMI of the subjects was between 18.5 and 24.9, accounting for 80.65% of the total, with 8.06% of the overweight sample and 11.29% of the underweight.

The experiment simulated light activities such as sitting, walking, and standing, specifically depicting a person transitioning from indoors to a bus stop to await a bus. The design of the human subjective thermal perceptions-related issues discussed in this study was available in English and Chinese. The subjective thermal sensation vote utilized a 7-point scale from ASHRAE [6], while both the thermal comfort vote (TCV) and the evaluation of personal emotions were based on a 5-point scale. For all experiment groups, the clothing insulation data from the subjects' personal information had a mean of 0.37 clo and a standard deviation of 0.09 clo, and hot season was 0.36, and for the transitional season, it was 0.39, calculated based on ISO 7730. Similarly, the metabolic rate data exhibited a mean of 1.2 Met [6, 7].

2.3 Measurement

In this study, a mini-weather station was employed to collect and record air temperature (T_a, °C), wind speed (v, m/s), and relative humidity (RH, %). The black globe temperatures (T_g, °C) were collected using black globe thermometers distributed to capture the environment parameters under the cooling spot and shading spot. During the field tests, instruments recorded values of all meteorological parameters every second. The mini-weather station and the black globe thermometers were positioned 1.6 m above the floor, aligning measurements with the person stands to capture microclimate parameters accurately.

During the microclimate parameter monitoring, surface temperatures of the radiant cooling panels and inlet and outlet water temperatures were logged at one-second intervals. Each radiant cooling panel's surface temperature (T_{sur}) was recorded using nine K-type thermocouples. PT100 sensors were employed to measure the inlet and outlet water temperatures. In this experiment, when the chiller setting temperature (T_{set})=8°C, the surface temperature (T_{sur}) is 14.3°C, T_{set}=12°C is 17.8°C and T_{set}=17°C is 21.9°C. In subsequent analyses, this study will use surface temperatures to characterize the controlled temperature changes of the experiments.

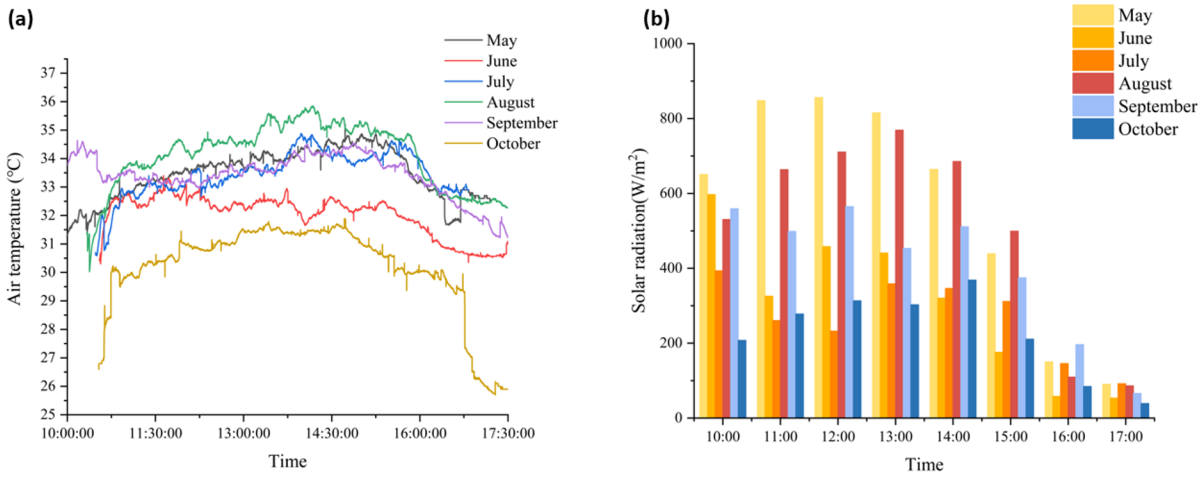

Fig. 2. Monthly outdoor weather parameter. (a) Air temperature （Monthly average）. (b) Solar radiation.

Table 1

Outdoors weather conditions recorded by the mini-weather station (Range/Average)

Month	Air temperature (T_a, °C)	Globe temperature (T_g, °C)	Relative humidity (RH, %)	Wind speed (v, m/s)	Solar radiation (SR, W/m²)
May	30.7-35.2/33.4	32.8-45.6/41.5	54.7-73.0/61.2	0-4.0/0.9	81-1021.5/619.3
June	30.3-34.4/32.9	31.2-43.5/36.6	53.3-74.0/67.9	0-4.0/0.7	20-926.5/273.1
July	30.6-34.9/33.5	33.7-45.3/38	55.2-72.5/60.7	0-3.2/0.7	76-1013/280.8
August	30-35.9/34	31.5-41.3/36.7	51.4-75/57.7	0-2.5/0.8	49.7-972/507.5
September	29.4-34.6/33.1	30.2-48/41.6	54.9-74/60.9	0-3.2/0.7	0-862.6/394.4
October	25.6-31.9/29.7	30.65-41.4/37.3	52-70/59.5	0-3.8/0.5	0-596.6/215.8

3. Result

3.1 Weather conditions of study location

According to the Koppen climate classification system [8], the climate of Hong Kong, China, belongs to the "Cwa," which means warm temperate monsoon climate, with hot-humid summers and cold-dry winters. Table 1 summarizes the microclimate conditions collected during the thermal comfort survey days at the experimental site. Fig. 2 shows the average outdoor T_a from 10:00 to 17:30 in six months and the average solar radiation value at different times. It can be noted that the T_a range and the average T_a are closed from May to September, while the average T_a is lower than 30°C in October: RH and v exhibit similar ranges and averages over these six months. In addition, the average solar radiation from May to September is higher than in October. The maximum solar radiation can reach values above 850W/m², whereas the maximum in October remains below 600W/m².

Based on weather data from the Hong Kong Observatory, the hot season in Hong Kong is from the end of May to the end of September [9]. By integrating weather data from this experimental mini-weather station and Hong Kong Obervation, May through September was categorized and labeled as the hot season, while October was classified as the transitional season.

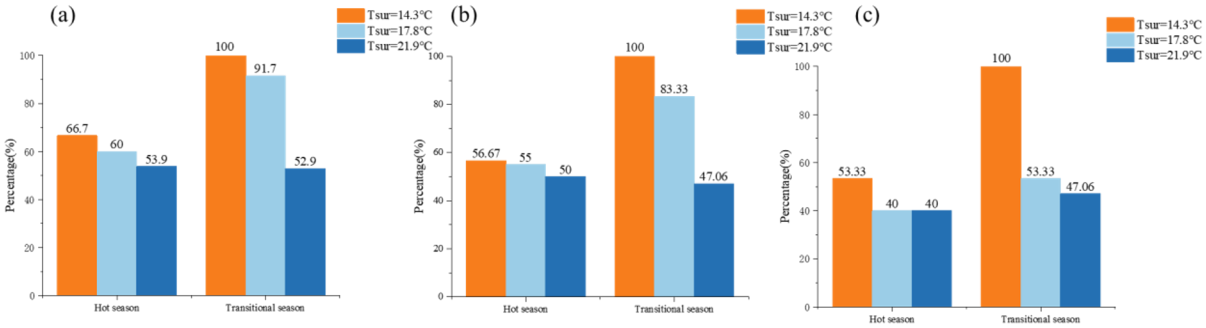

Fig. 3. Eligible ΔTSV Percentage of Total. Condition: (a) ΔTSV >0 (b) ΔTSV≥0.5 (c) ΔTSV≥1.

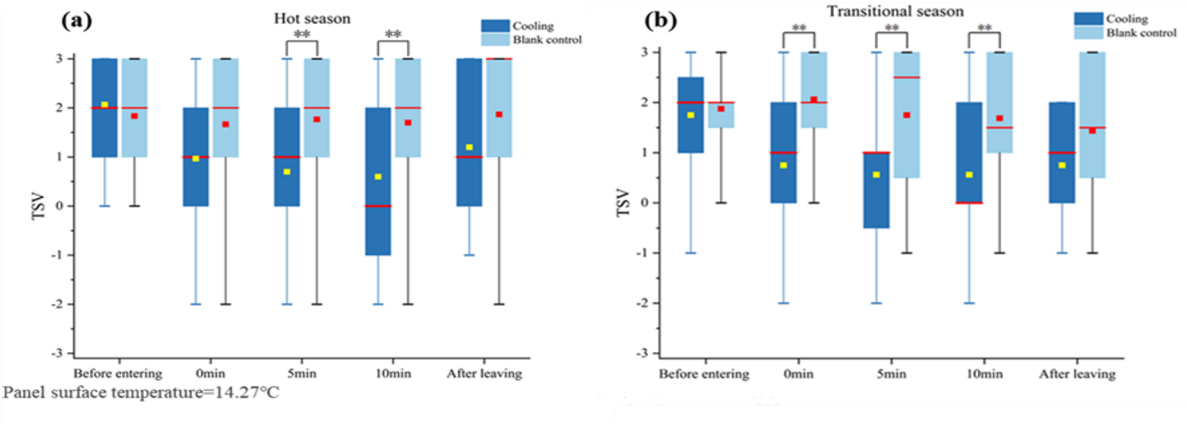

Fig. 4. Box plots comparing the blank control and cooling groups' TSV at various time points across different seasons at a panel surface temperature of 14.3°C. The box within the figure represents the TSV in the 25% to 75% range. (a) Hot season; (b) Transitional season

3.2 Overall thermal sensation

The ability of the cooling panels to lower the overall TSV in the same climatic conditions is an essential factor for evaluating cooling performance. In Fig. 3, ΔTSV is the difference between blank control groups and cooling groups' TSV with a 10-minute average value. This value represents the extent to which the cooling panel can reduce TSVs—comparing the three conditions of ΔTSV, i.e., ΔTSV>0, ΔTSV>0.5, and ΔTSV>1, in the hot and transitional seasons in different T_{sur}. As for ΔTSV>0 (Fig. 3(a)), the improvement percentage is decreased by the increase of T_{sur} at around 60% in the hot season, but in the transitional season, the improvement percentage for T_{sur} at 14.3 and 17.8°C is much greater than in the hot season with improvement percentages at 100% and 91.7%. And for T_{sur}=21.9°C, the improvement percentages both in the hot season and transitional season are quite similar, at about 53%. The percentage improvement decreases as the ΔTSV increases due to the limited cooling effect of the cooling panels during the hot season when panel temperatures are high. It is worth noting that during the transition season, the percentage improvement for T_{sur} of 14.3°C is 100%, even at the highest ΔTSV requirement (ΔTSV≥1). This suggests that lower T_{sur} is effective in reducing thermal sensations during the transitional season when air temperatures are cooler and solar radiation is lower. Moreover, even though the average value of clothing insulation in the transition season is 0.03 higher than that in the hot season, the thermal sensation is still reduced more in the transitional season, which indicates that a slightly higher clothing thermal resistance does not have much effect on the effectiveness of radiant cooling panels.

Fig. 4 demonstrates that human subjects standing under the cooling spot (T_{sur}=14.3°C) sustainably reduce the TSV during both the hot and transitional seasons. Fig. 4a illustrates a significant difference in TSV observed between the cooling and blank control groups after 5 minutes of exposure in the hot season. This indicates that the cooling effect can be rapidly percept. The concept of statistically significant difference is used here, and it is considered that there is a significant difference between the two groups of numbers at this moment. In the transitional season, a substantial reduction in TSV is immediately noticeable upon entering the cooling spot, as depicted in Fig. 4b. This shows human subjects' high sensitivity to temperature changes during the milder transitional season. It is noted that there is a decline in the sensation of coolness for the cooling group after leaving the cooling spot in the hot season. In contrast, in the transitional season, the cool sensation persists post-exposure. This phenomenon is attributable to the body's thermal lagging and the more temperate environmental conditions, which promote the preservation of the cool sensation during the transitional season, indicating that the thermal advantages of the cooling spot endure longer in less extreme temperatures.

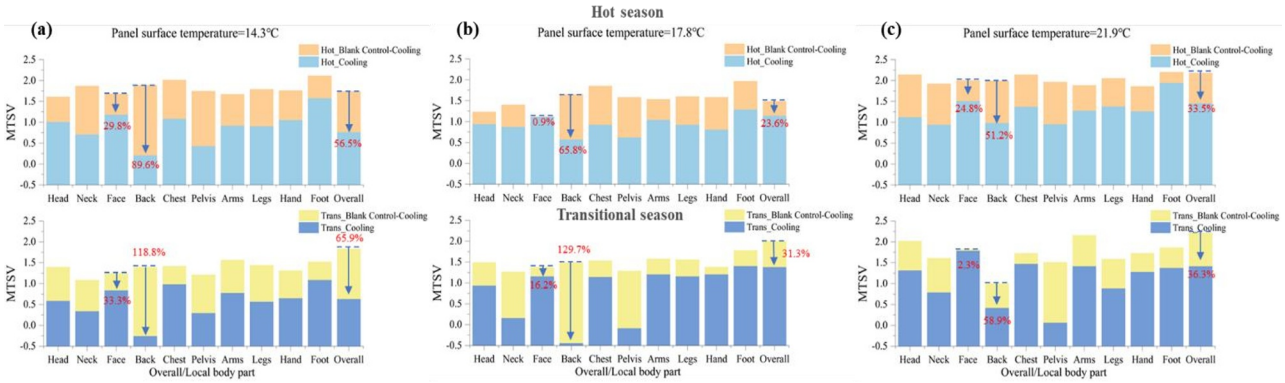

Fig. 5. Comparison of overall & local MTSV in blank control and cooling groups across conditions. (a) Panel surface temperature=14.3 °C; (b) Panel surface temperature=17.8°C; (c) Panel surface temperature=21.9°C.

3.3 Local thermal sensation

Understanding the local thermal comfort of human subjects is beneficial for comprehending the impact of cooling spot on various local body parts. This aids in developing superior comfort solutions to enhance overall thermal comfort. Under different seasonal and temperature conditions, the MTSV of the cooling group showed a significant lower compared to the blank control group, as illustrated in Fig. 5. Notably, the MTSV during the transitional season was lower than in the hot season, particularly at T_{sur}=14.3°C. In these conditions, the overall MTSV reduction was 56.5% in the hot season and 65.9% in the transitional season, respectively.

Further investigation into the cooling effects on specific body parts revealed that the back trunk (including the back, pelvis, and neck) experienced the most significant reduction in thermal sensation. Conversely, the face, foot, and hands showed relatively slight effects. A pronounced decrease in MTSV at the back was observed in both seasons at T_{sur}=14.3°C, with an MTSV reduction exceeding 89.6%. In contrast, the decrease in MTSV for the face was less, with a minimal reduction of 0.9%. The proximity to the radiant cooling panel (i.e., the back, neck, and pelvis) led to a more sharply decreased MTSV, whereas its effect on other body parts was less pronounced. This indicates even though a degree of thermal asymmetry in subjects stood under the cooling spot, the thermal comfort generated by the cooling of the back trunk offsets the feeling of being in thermal discomfort on the front side of the body, such as the face, head, and chest, thus allowing the overall TSV to be reduced. Overall, utilizing a cooling spot can be more effective during the transitional season, as it has a significantly greater cooling effect on people.

4. Conclusions

The thermal comfort performance of a membrane-assisted radiant cooling system is experimentally investigated. The analysis in this study is based on data from simultaneous microclimate measurements and questionnaire surveys conducted in subtropical Hong Kong. The following conclusions are drawn from this study:

1. The percentage improvement in overall TSV decreased as the ΔTSV increased. Notably, the panel surface temperature of 14.3°C resulted in improvement in TSV for all subjects during the transitional season.

2. The cooling effect of the panels is immediately felt and noticed at T_{sur}=14.3°C, with a notable difference in TSV within 5 minutes of standing under the cooling spot in the hot season. In transitional seasons, this cool sensation appears instantly and lasts longer after leaving the cooling spot, demonstrating both rapid onset and sustained effect of cooling.

3. The cooling spot provides a significant cooling sensation in the hot season. It is more effective during the transitional season, as evidenced by the higher percentage reduction in MTSV. This may be attributed to the mild ambient conditions during the transitional season, which results in a better cooling performance when combined with cooling spots.

In conclusion, a cooling spot based on radiant cooling panels can provide human thermal comfort in various thermal environments. However, only those with a certain degree of heat tolerance sign up for the experiment, which may lead to some limitations in the results. Meanwhile, there were subjective differences between subjects, and it is recommended that subjects be categorized through pre-experimentation and that the influence of psychological factors be taken into account. In addition, the survey bridges the gap in using radiant cooling systems in outdoor environments to improve human thermal comfort and provides a reference for subsequent research.

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