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Heating behavior using household air-conditioners during the COVID-19 lockdown in Wuhan: An exploratory and comparative study

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Abstract

Wuhan is located in China’s hot summer and cold winter (HSCW) zone, where the average temperature of the city from January to February 2020 is only 6.6 °C. This study aimed to explore and compare the air conditioner (AC) heating behavior of Wuhan residents before and after the COVID-19 lockdown. The date of commencement of the Wuhan lockdown (January 23, 2020) was considered the demarcation point to divide the AC monitoring data from the Internet of Things cloud platform into two groups; before and after Wuhan lockdown. Statistical methods were applied to analyze AC heating behavior of Wuhan residents from a total of 378 air conditioners during these two periods. The daily AC usage rate and average daily AC usage duration following the lockdown had a stronger correlation with daily outdoor temperature than that before the lockdown. AC heating behavior continued to demonstrate a part-time intermittent operation during the lockdown period, despite residents staying at home for a longer period. Trigger temperatures for occupants to turn on or adjust their AC during the lockdown period were overall 1–2 °C higher than before the lockdown. The AC heating demand in the HSCW zone has been increasing in recent years. These research results inform research on household energy demand and thermal comfort in China’s HSCW zone, and provide a reference on the household behavioral changes in the occupants in the context of a lockdown as a result of the global COVID-19 pandemic.

1. Introduction

1.1. Background of Wuhan lockdown

From January 2020, Wuhan confronted an epidemic caused by the coronavirus disease 2019 (COVID-19). To prevent the transmission of the virus, the Wuhan government issued an order to lockdown the city on January 23, 2020; whereby from 10AM on this date the urban bus, subway, ferry, and long-distance passenger transportation were suspended, and the airport and railway stations were temporarily closed. Citizens were instructed not to leave Wuhan unless there were exceptional circumstances. The government then issued a series of policies to stem the spread of the virus, including ceasing the operation of online taxis, implementing motor vehicle prohibition and management measures, closing non-essential public places, and implementing close management of community [1].

A series of imposed lockdown measures resulted in the citizens remaining within their residence in Wuhan for home quarantine. Social distancing was practiced by canceling events and gatherings, closing public places, schools, and universities. With the onset of rigorous lockdown management, the outdoor activities of residents were extremely limited. During the community lockdown management period, residents were able to only procure daily supplies either online, or via distribution in supermarkets and shopping malls. Community volunteers were able to provide basic services such as purchasing food and medicines. As such, from January 23rd to April 8th, 2020 (the day Wuhan was reopened) a large proportion of Wuhan residents stayed at home and rarely ventured outside.

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1.2. Heating demand in hot summer and cold winter (HSCW) zone of China

China has been divided into five climatic zones: the (1) severe cold; (2) cold; (3) hot summer and cold winter (HSCW); (4) hot summer and warm winter; and (5) temperate zones. Among these five zones, only the severe cold and cold zones in northern China have a district heating system (DHS). The DHS is a network heating systems that consists of a boiler plant (heat supply units), hot water pipeline (distribution networks), and radiators (user terminals). Under this system, hot water or steam is supplied to multiple buildings by a local boiler plant [2]. Compared with the severe cold and cold zones of China, the HSCW zone does not have a DHS; however, in this zone the average outdoor temperature of the hottest month is 25–30 °C, and that of the coldest month is 0–10 °C [3, 4]. Despite these relatively mild temperatures, the residents in this area still have heating requirements from time to time.

Previous studies have indicated that the indoor thermal environment in the HSCW zone is not within the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) comfort zone, where on average, indoor temperatures are 3–6 °C lower than those in cities in other parts of China [3, 5]. Li et al. [6] showed that in the HSCW zone, indoor air temperature is strongly influenced by outdoor temperature due to poor building performance (e.g., poor building insulation and infiltrations), and occupant behavior (residents within this zone open windows even in winter). A large-scale survey by Li et al. [6] reported that in the HSCW zone, the lowest indoor temperature of free-running (non-AC used situation) buildings in winter was only 2 °C, and the indoor temperature of free-running buildings within the ASHRAE comfort zone only accounted for 5% of the winter duration, which is considerably lower than the relevant standards. Similar results were reported by Guo et al. [7], that found that the indoor temperatures of unheated rooms were approximately 12 °C and those of heated rooms were approximately 15 °C. Exposure to a low indoor temperature environment for a long time has a negative impact on human health [8]. Collins [9] reported that low ambient temperature (below 16 °C) increases the risk of respiratory infections. When the ambient temperature is below 12 °C, blood pressure increases, as does the winter mortality caused by heart attacks and strokes [9]. In addition, occupant productivity has been found to decrease in an uncomfortable indoor thermal environment [10–12]. Therefore, space heating in the HSCW zone in China is an important topic closely related to health and well-being of residents.

In contrast to the DHS in Northern China, which cannot be adjusted by terminal users and continuously supplies heating water for 24 h, previous studies have shown that personalized dispersed heating systems that may be flexibly adjusted by users, are more suitable for climate conditions in HSCW [13,14]. Currently, residents in the HSCW zone typically use a dispersed heating system to meet their heating requirements [7]. The main types of dispersed heating equipment used in this zone include local electric heaters, split air conditioners, domestic central air conditioners (variable refrigerant volume systems), and gas boilers [13]. Among these heating systems, the split air conditioner is the most widely used appliance for winter heating in the HSCW zone [13,15]. In recent years, they have been used more frequently and over longer durations in the HSCW zone as the residents have greater expectations for improved indoor temperature and comfort [13]. The use of a dispersed heating system means that residents are able to operate their dispersed heating equipment individually and flexibly based on their dynamic demand as opposed to the continuous 24 h operation as per the DHS in northern China. This has meant occupant behavior has become a significant topic in dispersed heating and cooling systems, where varied and complex behavior introduces many challenges [16].

1.3. Occupant behavior of air conditioning heating in HSCW zone

The occupant behavior of air conditioner (AC) heating demand, such as set-point temperature and duration, significantly impacts the consumption of residential heating energy [17,18]. To examine the heating demand of occupants, particularly in the winter in the HSCW zone, previous researchers have used a large-scale questionnaire [15,19], and small-scale field monitoring methods [19,20] to explore how socio-demographic [21,22], occupancy [19,23–25], thermal experience [20,26,27], and psychological factors [21,22] influence AC heating behavior. Their findings show that time and indoor temperature were the most important factors that triggered residents to turn on AC for heating. Heating usage patterns of AC heating were intermittent as a type of ‘part-time-part-space’; this is completely distinct from continuous heating usage pattern of central heating systems in northern China [7,15,20].

In particular, occupancy behavior, considered the main factor resulting in the diversity of heating behavior [7], was always an important factor considered in studies related to AC heating behavior. For instance, to analyze occupant AC behavior, the foremost aspect to understand was the occupancy pattern [19,23–25]. Wang et al. [19] proved that heating occurs only when the occupants are at home, and the indoor temperature is lower than the heating trigger temperature. This study also showed that households with retired residents required longer heating duration. This implies that that the longer people stay at home, the longer they use AC.

As such, current studies show that there was no specific pattern of occupancy behavior when researchers investigated occupant AC heating behavior. This means that due to various circumstances in occupancy patterns, existing research on heating behavior via air conditioners essentially demonstrated the combined effects of occupancy behavior and environmental conditions. Findings showing that residents within the HSCW zone in China preferred a ‘part-time’ AC heating mode was also premised on circumstances in which residents did not need to stay at home for long periods; residents had the freedom to go outside. It is impossible to know whether this conclusion is suitable for situations in which residents are required to stay at home at all times. In the context of the Wuhan lockdown, it is possible to examine the AC heating behavior as a fixed occupancy behavior without considering various occupancy patterns.

1.4. Study objective

This study aims to address the following research questions:

1) What was the behavior toward using AC-based heating for Wuhan residents during lockdown?
2) Were there significant differences in the AC heating behavior before and after the Wuhan lockdown? If so, what were these differences?
3) Does intermittent AC heating operation pattern also occur when people stay at home for a long time?

2. Methodology

2.1. Introduction of research samples in this study

Wuhan is located in the HSCW zone of China. The average temperature of Wuhan from January to February, 2020, was only 6.6 °C [28]. January 23, 2020 (when the lockdown policy became effective), was considered the point in time to split the time series data into two groups. One group was the monitoring data prior to the Wuhan lockdown (January 1, to January 22, 2020), whilst the other was the monitoring data after the Wuhan lockdown (January 24, to February 14, 2020). To ensure the validity of selected samples, ACs that were in operation before and after the lockdown of the city were selected as the research samples; this equates to a total of 378 air conditioners that were used this study. These 378 ACs were randomly sampled and distributed in Wuhan. The process between each turning on action and turning off of each AC was recorded as a single operation (per operation). Prior to the
lockdown, the 378 ACs had a total of 9406 operations, whilst there were 9207 operations after the Wuhan lockdown.

All data processing and analyses in this study were run using Python 3.7.

2.2. Data collection

Data used for this study was obtained from the monitoring data of the IoT cloud platform of a Chinese AC equipment manufacturer. The original data included a time series of real-time monitoring of AC usage from January 1 to February 29, 2020, in Wuhan, China (the data from January 1 to February 14, 2020, was selected for this study). The data mainly includes the on/off status of the ACs, set-point temperature, indoor temperature, and accumulated operating time. The indoor temperature sensors were located at the return air outlet of the AC as opposed to the central part of the room. This differs from studies using field measurements to measure indoor air temperature. The outdoor weather data was downloaded from a public website (https://rp5.ru/), and the data record interval for this outdoor weather data was 3 h [28].

2.3. Data pre-processing

The original data of this study consisted of time-series data. Two key processes were required for this data to be conducive for analysis to meet the aims of this study:

1) Recognition of AC behavioral characteristics: identifying the actions of the occupant in terms using the AC operation characteristic parameters from the time series data. This meant that using the time series operation status or set mode status data, we needed to identify occupant behavioral traits for each operation including on/off behavior, temperature setting adjustments, and the duration of the AC operation.

2) Resampling and aggregation statistics of AC monitoring data: the sampling interval of the raw monitoring data was not fixed. The original data needed to be resampled such that the time interval matched to ensure the reliability of the conclusions.

3. Results

This section is mainly composed of two parts. First, we introduce the overall use of ACs in Wuhan from January to February 2020; this includes the overall usage rate, the average daily duration of AC use, and the relationship between the overall AC use and outdoor environmental parameters. We compare these characteristics before and after the Wuhan lockdown. Second, we analyze AC usage pattern, including the duration in a single operation, and the relationship between AC actions with indoor temperature and set-point temperature behavior. We then compare these characteristics before and after the Wuhan lockdown.

3.1. Relationship between outdoor temperature and overall air conditioning heating behavior

The outdoor temperature is highly related to overall AC usage [29–33]. To explore which statistic of outdoor temperature was more closely related to the overall AC usage, we collected three statistics relating to outdoor temperature; the daily maximum, the daily minimum, and the daily average. Then, we calculated the Spearman correlation coefficient for these three values with the daily usage rate and duration. The results are summarized in Table 1.

The results revealed that the daily mean outdoor temperature had a stronger relationship with the daily usage rate, whilst the daily maximum outdoor temperature was more closely related to the daily duration of AC usage.

| Outdoor temperature | Daily usage rate | Daily duration time |
|---------------------|------------------|---------------------|
| Minimum             | −0.48            | −0.33               |
| Mean                | −0.77            | −0.72               |
| Maximum             | −0.74            | −0.80               |

3.1.1. Relationship between outdoor air temperature and air conditioning daily usage rate

1 Regression model

We defined the daily usage rate as Eq. (1):

\[ DUR = \frac{\text{Number of air conditioners used in one day}}{\text{Total number of air conditioners in this research}} \]  

The logistic regression model is a traditional approach used in previous research to fit the relationship between the AC usage percentage and environmental parameters [30]. In this study, the logistic model with the least squares method was applied to fit the regression model relating the daily outdoor temperature and daily AC usage rate. The fitness curves are shown in Fig. 1, and the fitting formulas are presented in Eq. (2) and (3). As this regression model was developed based on limited outdoor temperature records, the model is only effective at the available outdoor temperature interval. The intersection point at which Eq. (2) and (3) were equal (7.3°C, 0.68) was within the effective temperature interval. This means that at the same outdoor temperature, when \( T_{\text{out,mean}} \) is less than 7.3°C, the daily usage rate following the lockdown was greater than before the lockdown. In contrast, the daily usage rate after the lockdown was less than before the lockdown when \( T_{\text{out,mean}} \) is greater than 7.3°C.

Before Wuhan lockdown:

\[ DUR = \frac{1}{1 + e^{(0.666 + 1.25)}} \quad (R^2 = 0.25) \quad (1.5 \leq T_{\text{out,mean}} \leq 8.8) \]  

After Wuhan lockdown:

\[ DUR = \frac{1}{1 + e^{(1.322 + 1.25)}} \quad (R^2 = 0.60) \quad (3.3 \leq T_{\text{out,mean}} \leq 13.5) \]  

2 Comparative analysis before and after lockdown

Although the R^2 (also known as the goodness of fitness) after the Wuhan lockdown (R^2 = 0.60) was much higher than before Wuhan lockdown (R^2 = 0.25), these comparative results may not be entirely reliable because of the inconsistent range of outdoor temperatures before and after lockdown. The daily outdoor temperature after lockdown spanned a wider range and was higher than before lockdown. To eliminate the differences in outdoor temperature, the range of outdoor temperature that had both occurred before and after the Wuhan lockdown was used. This meant that the differences between outdoor temperature and daily usage rate before and after lockdown could be compared within the same temperature ranges. For example, the range of daily mean outdoor temperature before lockdown was between 1.5 and 8.8°C, whilst this range after lockdown was between 3.3 and 13.5°C. As such, we selected the daily usage rate at daily outdoor temperatures between 3.3 and 8.8°C to compare differences before and after lockdown. We defined values of \( T_{\text{out,mean}} \) before and after lockdown as Group1 and Group2 respectively. To ensure the reliability of the comparative analysis, a difference analysis (independent t-test) between Group1 and Group2 was adopted to ensure that the outdoor temperature distributions before and after the lockdown were the same. First, the normality test (Shapiro–Wilk test [34]) and homogenous test of variance (Bartlett’s test [35]) were applied to identify whether parametric tests are normally distributed and homogenous.
could be used to compare differences between these two groups. Then, an independent t-test was used to detect whether there were significant differences in the daily outdoor temperature distribution before and after lockdown. The p-values of the hypothesis tests are presented in Table 2, showing that there were no significant differences in the daily mean outdoor temperature distribution before and after lockdown. Based on this, the Spearman correlation test was used to compare the relationship between outdoor temperature and daily usage rate under specific outdoor conditions (between 3.3 and 8.8 °C) before and after lockdown. The null hypothesis for the Spearman correlation test was that the two datasets were not correlated; as such, a p-value <0.05 indicates that these two datasets are correlated at a significance level of 0.05. The results in Table 3 show that when the daily mean outdoor temperature was between 3.3 and 8.8 °C, the negative correlation between AC daily usage rate and outdoor temperature after the lockdown was much higher than before the lockdown. This may be because during the lockdown, occupancy status had become increasingly fixed than before the lockdown. As such, outdoor air temperatures accounted for most of the influence on the usage rate in situations where occupants are always at home.

### 3.1.2. Relationship between outdoor air temperature and daily duration of air conditioning

First, we defined the daily duration (DD) of AC as the average of all operated air conditioners (only including air conditioners where duration exceeded 0 h on the examined day) on a natural day, as shown in Eq. (4):

\[
DD = \frac{\sum DD_i}{N}
\]  

(4)

where.

- \(DD_i\) represents the duration of the \(i\)th air conditioner in one natural day;
- \(N\) represents the number of air conditioners whose duration in this natural day exceeds 0 h.

Fig. 2 shows the relationship between the daily duration of the AC and the daily maximum outdoor air temperature. There is a clear linear relationship between the AC duration and daily maximum outdoor air temperature. The results of the linear fitting (p < 0.01) are also shown in Eq. (5) and (6). As this regression model was developed using limited outdoor temperature samples, the model was only effective at the available outdoor temperature interval.

Before Wuhan lockdown:

\[
DD = -0.161T_{\text{out, max}} + 7.72 (R^2 = 0.44) \quad (2.4 \leq T_{\text{out, max}} \leq 12.2)
\]  

(5)

After Wuhan lockdown:

\[
DD = -0.31T_{\text{out, max}} + 10.68 (R^2 = 0.90) \quad (4.0 \leq T_{\text{out, max}} \leq 18.6)
\]  

(6)

### 2 Comparison analysis before and after lockdown

As per the previous analysis of AC usage rate, to eliminate the difference in outdoor temperature range, the range of outdoor temperature that was applicable before and after the Wuhan lockdown was selected to compare differences in the relationship between outdoor temperature and daily AC duration before and after the lockdown. The range of daily maximum outdoor temperature before the lockdown was between 2.4 and 12.2 °C, whilst this range of daily maximum outdoor temperature after the lockdown was between 4.0 and 18.6 °C. As such, we selected the daily duration at a daily outdoor temperature range between 4.0 and 12.2 °C to compare differences before and after lockdown. We defined the \(T_{\text{out, max}}\) before and after lockdown as Group3 and Group4, respectively. To ensure reliability of the comparative analysis, a difference analysis between Group3 and Group4 was conducted to ensure that the outdoor temperature distributions before and after the lockdown were the same. The p-values of the normality test, homogenous test of variance, and independent t-test are shown in Table 4. There is no significant difference in the daily maximum outdoor temperature distribution before and after lockdown. As such, the Spearman correlation test was used to compare the relationship between outdoor temperature and daily duration of AC usage before and after lockdown under specific

![Fig. 1. Scatter plot and the logistic regression results of the relationship between AC daily usage rate and daily mean outdoor air temperature.](image-url)

![Fig. 2.](image-url)
outdoor conditions (between 4.0 and 12.2 °C). The results in Table 5 show that when the daily maximum outdoor temperature was between 4.0 and 12.2 °C, the negative correlation of AC daily duration with outdoor temperature after the Wuhan lockdown was much stronger than that before the lockdown.

3.2. AC usage patterns

3.2.1. AC heating duration

The duration of AC heating had a significant relationship with the function of the room; as such, we distinguished between floor standing air conditioners and wall mounted air conditioners for analysis. The floor standing air conditioners in this study were all split systems with a cooling capacity greater than 5000 W. The wall mounted air conditioners were all split systems with a cooling capacity less than or equal to 3500 W. In China, floor standing air conditioners are typically used in living rooms, although some homes also use wall mounted air conditioners in the living room. In general, wall mounted air conditioners are predominantly used in bedrooms. Fig. 3 shows the distribution of AC duration for the 9406 operations (a total of 378 air conditioners) before the Wuhan lockdown, and the 9207 operations after the Wuhan lockdown (a total of 378 air conditioners); floor standing and wall mounted air conditioners were opposite in terms of usage duration before and after lockdown.

The Kruskal-Wallis H-test [36] was used to test differences before and after lockdown. For floor standing air conditioners (always used in large rooms, generally in the living room), the test results confirmed that there was a statistically significant difference in the duration of operations before and after the lockdown (p < 0.01). The duration per operation after the lockdown was longer than before the lockdown. The median duration for each operation after the lockdown (225 min, 3.74 h) was 48 min longer than before the lockdown (177 min, 2.95 h). The average value (321 min, 5.35 h) was 76 min longer than before the lockdown (245 min, 4.13 h). The Cumulative Distribution Function (CDF) curve in Fig. 4 also illustrated similar patterns to Fig. 3 (note that this study only shows intervals between 0 and 30 h). Before the Wuhan lockdown, the proportions of AC duration for each operation that exceeded 3 and 6 h were 50% and 20%, respectively. After the Wuhan lockdown, these proportions had increased to 60% and 30%, respectively. For wall mounted air conditioners (always used in small rooms, mostly in bedrooms), the test results showed that there was no significant difference (p > 0.05) in AC duration before and after the Wuhan lockdown. Although residents were at home for a much longer period after the lockdown, the AC heating duration for each operation after the lockdown did not deviate considerably from that before the lockdown. The CDF curve in Fig. 4 also showed similar results. Before the Wuhan lockdown, the proportions of AC duration for each operation that exceeded 3 and 6 h were 50% and 20%, respectively. After the Wuhan lockdown, these proportions had increased to 60% and 30%, respectively. In contrast, after the Wuhan lockdown, these proportions were 49% and 29%, respectively.

We defined the proportion of times that the air conditioner was turned on at different times of the day (every hour of a day, from 00:00 to 23:00), as per Eq. (7):

\[
\frac{\text{Number of air conditioner operations started at the hour of } i}{\text{Number of total air conditioner operations}}
\]

(7)

where, i is each hour of a day, from 00:00 to 23:00.
Fig. 5 provides a comparison of the proportion of times the air conditioner was turned on at different times of the day, before and after the Wuhan lockdown. The occupant action of turning on the AC between 08:00 and 08:59 was recorded as 08:00. For wall mounted air conditioners, the two plots showed similar trends, indicating that there was little difference in the times that the air conditioners were turned on before and after the Wuhan lockdown. For floor standing air conditioners, the main difference before and after the lockdown was that there was a significantly higher proportion of the air conditioners being turned on between 09:00–12:00 after the lockdown. The peak of air conditioners being turned on was delayed by 2 h after the lockdown compared to before the lockdown (postponed from 08:00 to 10:00).

To determine whether there was an obvious difference in the duration for each AC operation based on air conditioners being turned on at different hours, we divided 24 h of a day into four time periods as follows:

1) Night: 00:00–05:59
2) Morning: 06:00–11:59
3) Afternoon: 12:00–17:59
4) Evening: 18:00–23:59

The median value of duration for each operation was calculated when the air conditioner was turned on in different time periods; these results are presented in Fig. 6. The results were completely different between floor standing and wall mounted air conditioners. For floor standing air conditioners, the duration for each operation after the Wuhan lockdown was longer than before the Wuhan lockdown, regardless of when the AC is turned on during the day. In particular, in the morning, the duration for each operation after the lockdown was greater than 1 h longer than before the lockdown. For wall mounted air conditioners, when the AC was turned on the duration for each operation after the lockdown was always lower than that before the lockdown. The exception to this pattern was when these air conditioners were turned on in the morning. The biggest gap in duration for each operation occurred at night; the AC duration after the lockdown had reduced by approximately 36 min compared to before the lockdown. These results suggest that during the COVID-19 lockdown, the heating duration in the morning had been increasing both for floor standing and wall mounted air conditioners, whilst the heating duration at night had been decreasing for wall mounted air conditioners.

After the lockdown, as residents in Wuhan stayed at home for a longer time, their AC heating schedule experienced some alterations compared to patterns before the lockdown. These alterations are better reflected in the usage patterns of floor standing air conditioners typically utilized in the living room, instead of wall mounted air conditioners. During lockdown, although the AC heating duration for floor standing air conditioners increased, this increase was much lower than the proportional increase in the amount of time residents stayed at home. An increase in heating duration mainly occurred in the morning. This indicates that even if residents stayed at home for a longer time, the usage patterns of AC heating continued to be intermittent; this reflects part-time heating. Although there are samples of long-term continuous operation, the CDF diagram in Fig. 4 illustrates that the proportion of these samples before and after lockdown were not significantly different. This means that although residents stay at home for longer periods of time, improvements to AC heating duration were still limited.

3.2.2. Occupant behavior of AC heating usage with indoor air temperature

In this section, we explore the indoor temperature thresholds of residents under various AC adjustment actions; these actions include turning on the AC, turning off the AC, turning up the set-point temperature, and turning down the set-point temperature. This means that we would discuss and compare the difference in indoor air temperatures that trigger these adjustment actions before and after the Wuhan lockdown. The Kruskal-Wallis H-test results confirmed that there were statistically significant differences ($p < 0.01$) in the indoor temperature thresholds of residents before and after the lockdown. Table 6 presents the statistics of the indoor temperature threshold distribution of these four actions before and after the Wuhan lockdown. The results show that regardless of the adjustment action, the indoor temperature threshold distribution after the lockdown was higher than that before the lockdown.
lockdown. The increase in the average trigger threshold for turning on the AC was approximately 2.0 °C (from 14.3 to 16.3 °C). The increase in the average trigger threshold for turning up the set-point temperature was approximately 1.9 °C (from 17.0 to 18.9 °C). The increase in the average trigger threshold for turning down the set-point temperature was approximately 1.2 °C (from 20.6 to 21.8 °C), whilst the increase in the average trigger threshold for turning off the AC was approximately 1.3 °C (from 21.7 to 23.0 °C). These results demonstrate that when residents stay at home for a long period of time, this impacts their trigger threshold of indoor temperature that influences their behavior in AC usage. It can also be deduced that when residents need to stay at home for a long period of time, their lower indoor temperature threshold and the indoor temperatures that induce adjustment of the set-point temperature have slightly increased by approximately 1–2 °C. This indicates that residents in Wuhan have higher comfort temperature during the lockdown period than their typical situation (before the lockdown).

Additionally, the increase in the temperature threshold to prompt turning on the AC and turning up the set-point was slightly higher than the temperature threshold to turn off the AC and turn down the set-point.
point. This means that during the lockdown, the lower tolerance limit of indoor temperatures for residents had increased more compared to the upper tolerance limit.

The trigger indoor temperature that prompts residents to turn on the AC has always been a key concern in previous studies. Studies have found that residents turn on AC heating when the indoor air temperature...
drops below their lowest acceptable temperature \cite{19, 20}, which is also known as the heating-triggering temperature. These results were based on single operations of the total investigated air conditioners. In this study, we aggregated the behavioral data on a single air conditioner level (that is, to take each air conditioner as the index for aggregate statistics), and then compared the indoor temperature that triggered occupants to turn on the AC before and after the Wuhan lockdown. The CDF curves of the trigger temperatures relating to the 378 air conditioners in terms of turning on the AC before and after the Wuhan lockdown are shown in Fig. 7; the differences between the two periods are evident. After the city lockdown, the CDF curve shifted to the right. Previously, the proportion of samples in which the trigger temperature

Table 6
Statistics on the indoor air temperature threshold when different adjustment actions (i.e., turning on AC, turning off AC, turning up and turning down set-point temperature) (°C).

| Turning on AC     | Turning off AC       | Turning up set-point temperature | Turning down set-point temperature |
|-------------------|----------------------|----------------------------------|-----------------------------------|
| Before Wuhan      | After Wuhan          | Before Wuhan                     | After Wuhan                       |
| lockdown          | lockdown              | lockdown                          | lockdown                          |
| Mean              | 14.3                 | 21.7                             | 17.0                              | 20.6                              |
| Median            | 13.9                 | 21.4                             | 15.9                              | 20.3                              |

Fig. 6. Comparison of the median duration of each operation turned on at different times throughout the day for floor standing and wall mounted air conditioners.

Fig. 7. The CDF curves of the trigger temperatures relating to the 378 air conditioners in terms of turning on the AC before and after the Wuhan lockdown.
was higher than 13 °C accounted for only 60%, whilst this was 80% after the city lockdown. After the lockdown, 60% of samples had a trigger temperature exceeding 15 °C.

3.2.3. Temperature setting behavior of AC heating

We used 30 min as the minimum aggregation period to obtain statistics on the set-point temperature of all investigated air conditioners every half hour (that is, the set-point temperature of each air conditioner every 30 min was a sample in this analysis). Fig. 8 shows the set-point temperature distribution before and after the lockdown, whilst Fig. 9 shows the average and median values of the set-point temperatures for each hour of the day.

The set-point temperatures after the lockdown were lower than that before the lockdown, and the proportion of set-point temperatures greater than 26 °C after the lockdown had significantly reduced. A decrease in the proportion of set-point temperatures of 29–30 °C was particularly evident. In contrast, the proportion of set-point temperatures of 20–24 °C had increased significantly. After the lockdown, most times during the day, the median set-point temperature was 1 °C lower than at the same time before the lockdown (from 26 to 25 °C).

We also used each air conditioner as the analysis object (with a total of 378 air conditioners), and calculated the average set-point temperatures for each air conditioner before and after the lockdown (each air conditioner was a sample in this analysis). The results illustrate that 61% of air conditioner users had a lower set-point temperature during the lockdown compared to before lockdown.

Regardless of the lockdown, the set-point temperature in some time periods in the morning and afternoon were 0.5–1.5 °C lower than the set-point temperatures between 18:00 to 09:00. The fluctuations in the set-point temperatures with time of day after the lockdown had reduced compared to before the lockdown.

In summary, the demand for setting a relatively higher set-point temperature had reduced after the lockdown compared to before the lockdown. Under normal conditions, a high set-point temperature demand generally means that occupants want the room to heat up rapidly. However, after the lockdown, the demand for high set-point temperatures decreases, indicating that the demand for rapid indoor temperature rise has reduced when staying at home over long periods of time.

3.3. Comparison with previous studies in HSCW zone

3.3.1. Air conditioning heating duration

Lin et al. [20] showed that the majority of AC heating was triggered between 16:00 and 19:00 for the living room, and between 19:00 and 22:00 for the bedroom; this study also observed similar results (Fig. 5). It was also observed that the proportion of heating operations in the morning was not dependent on before or after the lockdown. Fig. 5 shows that for floor standing air conditioners (always used in the living room), the proportion of operations triggered between 08:00 and 12:00 was relatively high compared to other times. For wall mounted air conditioners, the proportion of operations triggered between 07:00 and 09:00 was also relatively high level compared to other times.

In terms of heating duration, in the living room and bedroom, the duration per heating operation (presented in Table 7) was longer than that found in Lin et al. [20] (i.e., 2.3 h per operation for the living room; 2.8 h per operation for the bedroom). This means that the AC heating demands of residents within the HSCW zone have increased in recent years.

3.3.2. Air conditioning heating trigger temperature

Lin et al. [20] shows that the majority of people in the HSCW zone would trigger AC heating when the indoor temperature is between 10 and 14 °C; this was also observed in Chen et al. [38] who reported that at the beginning of heating, the indoor air temperature was between 9 and 15 °C. In this study, the heating trigger temperatures before and after the lockdown, were higher than these previous studies. We deduced that there may be three key reasons for this shift in behavior. First, different cities in the HSCW zone may have different air-conditioning behaviors. The results from Lin et al. [20] were based on investigations in Nanjing and Shanghai, whilst Chen et al. [38] was based on investigations in Hangzhou. These three cities are located downstream of the Yangtze River. This study is based in Wuhan, located at the mid and lower reaches of the Yangtze River. Previous studies have also shown that there are divergences in the AC behavior [39] and energy usage [19] of residents in different cities in the HSCW region. Second, the differences may have been caused by the differences in the installation location of the indoor air temperature sensor. The indoor air temperature sensor investigated in this study was embedded in a split air conditioner where it was located at the return air outlet of the air conditioner; this is at the upper part of the room for a wall mounted air conditioner and at the bottom of the room for the floor standing air conditioner. In contrast, the indoor air temperature sensors used in other field measurement studies were always in the center of the measured rooms.

3.3.3. Air conditioning heating set-point temperature

Wang et al. [19] illustrated that around half of the households set heating temperatures between 16 and 20 °C. However, the results of our study (Fig. 10) show that only about 10% of the investigated air conditioners were set below 20 °C, whilst more than 60% of samples set their heating set-points above 24 °C. This indicates that in the last five years, with economic growth, a greater number of residents are setting a higher set-point temperature for AC heating.

4. Discussion

4.1. Potential reasons of behavioral changes

An important observation based on these analyses is that during the lockdown for residents in Wuhan, the indoor air temperature range that was tolerated by residents has evidently shifted. During the lockdown, the indoor air temperature that prompted residents to turn their AC heating on had increased in comparison to before the lockdown. Previous studies have indicated that residents turn on AC heating when the indoor air temperature drops below their lowest acceptable temperature [19,20]. The results of this study show that after the lockdown, the lowest indoor temperature that occupants tolerated was 2 °C higher than before the lockdown; this shift may be attributed to various potential reasons.

During the lockdown, due to the rigorous lockdown policy, residents
in Wuhan had to stay in the indoor environment over a very long time and rarely ventured outside of their homes. This may affect the thermal comfort of occupants in two ways. First, the routine activity levels of residents may be lower than before the lockdown. Based on the metabolic rate in the ASHRAE Handbook [40], different activities induce significantly different metabolic rates. For instance, the metabolic rate of reading while seated was only 55 w/m², whilst the metabolic rate of walking was 100 w/m². As such, it is likely that due to restrictions, Wuhan residents were constantly at a lower metabolic rate, induced by activities such as sitting or sleeping for a long time during lockdown. According to a review by Luo et al. [41], a change in metabolic rate affects the thermoregulatory responses of the body. For example, the neutral skin temperature decreases with increasing activity [42]. Thus, the reduction in metabolic rate when people remain at home for a long period of time may affect the thermal comfort temperature of occupants. Additionally, residents had limited access to the outdoor environment due to restrictions. Previous research has shown that the thermal adaptability of a person would alternate when exposed to a comfortable thermal environment over the long-term. For instance, Luo et al. revealed that long-term comfortable thermal experiences increase the thermal expectations of a person, whilst a non-neutral environment stimulates their thermal adaptability [43]. Long-term indoor thermal exposure during the space heating period may also impact on human thermal adaptability [44]. A longer occupancy period in an indoor space leads to a higher comfort temperature [45]. After adaptation to this thermal environment, residents may become more sensitive to temperature drops, causing more discomfort of cooler temperatures [46]. Therefore, we deduce that the thermal adaptability of residents in Wuhan may have changed due to their long-term exposure to the indoor thermal environment. This has led to an increase in the trigger temperature prompting them to turn on AC heating.

Wuhan residents also experienced substantial psychological pressure during the lockdown [47]. A psychological health investigation of Wuhan residents from February 18 to 28, 2020 [48] reported that during the COVID-19 pandemic, of 1242 Wuhan residents, 27.5% had anxiety, 29.3% had depression, 30.0% had a sleep disorder, and 29.8% exhibited a passive response to COVID-19. This investigation [48] also showed that the prevalence of psychological problems among Wuhan residents during this period was higher than that of the whole population. These circumstances, characterized by a lack of vaccines, unpredictability, and the indefinite quarantine period, placed tremendous pressure on Wuhan residents. Isolation and widespread economic losses had triggered a range of psychological issues for many people [49]. Additionally, the shortage of medical resources had cultivated a fear among Wuhan residents of getting sick. Accordingly, they experience significant anxiety regarding their health problems during this period, especially when experiencing symptoms such as colds, fever, cough, and runny nose. One study showed that the temperature steps were related to the health issues experienced by occupants associated with the nervous, digestive, and respiratory systems [50]. As such, we deduced that residents in Wuhan may be more inclined to turn on their air conditioner despite the indoor temperature not deviating substantially from their comfort zone as they were afraid of catching a cold. This would create a comfortable environment for themselves and reduce the risk of illness.

In summary, the reasons underpinning the change in the heating

Table 7
Statistics on the duration per heating operation in Wuhan (h).

|                          | Before Wuhan lockdown | After Wuhan lockdown |
|--------------------------|-----------------------|----------------------|
|                          | Median    | Average  | Median    | Average  |
| Floor standing air conditioners | 2.95      | 4.13     | 3.74      | 5.35     |
| (mostly used in the living room) |          |          |           |          |
| Wall mounted air conditioners | 3.04      | 5.72     | 2.96      | 5.52     |
| (mostly used in the bedroom) |          |          |           |          |

Fig. 9. The fluctuation in set-point temperatures at different times during the day.

Fig. 10. The CDF curve of the average set-point temperature of a total of 378 air conditioners before and after the Wuhan lockdown.
trigger temperature are complex and multi-faceted, and as such, warrants further examination in future research.

4.2. Increased air conditioning heating demand in recent years

Comparing the research results [19,20] with previous years, the demand for AC heating in the HSCW area has significantly increased regardless of heating duration [20] and set-point temperature [19]. This is consistent with previous related studies that had postulated that alongside economic improvements the demand for AC heating would substantially increasing. The improvement in the heating demand of the HSCW zone will considerably elevate heating energy consumption. As such, future research should focus on ways in which to decelerate the increasing trend of residential heating energy consumption whilst meeting the thermal comfort and health requirements of occupants.

The results from previous studies also found that residents in the HSCW zone only turn on air conditioners in winter when they feel cold. For example, Cui et al. [51] found that the majority of residents in the HSCW zone in China used AC systems only in winter when they were cold. However, in the HSCW zone, the trigger temperature of turning on AC heating has significantly increased. This may mean that the behavior of residents has changed to turning on air conditioners only when they feel cold, which begs the question as to whether there are other demands for AC heating. This is also a knowledge gap that requires further attention in future research.

5. Conclusions

Wuhan was confronting a COVID-19 pandemic at the beginning of 2020. To prevent the spread of the disease, the Wuhan government issued a lockdown order on January 23, 2020. During the lockdown period, a series of imposed lockdown measures meant that the residents of Wuhan were to strictly adhere to home quarantine. Under these circumstances, residents in Wuhan stayed at home for long periods of time and rarely ventured outside of their homes. The main purpose of this study was to explore AC heating behavior when under these unique circumstances (i.e., the city lockdown), and compare AC usage behavior before and after the lockdown. According to the time in force of the Wuhan lockdown (January 23, 2020), the long-term monitoring data from January 1, 2020, to February 14, 2020, of air conditioners in Wuhan from the IoT platform were divided into two groups (before Wuhan lockdown and after Wuhan lockdown). Statistical methods were used to explore and compare the AC heating behavior of Wuhan residents based on a total of 378 split air conditioners during these two time periods. The key conclusions from this study are as follows:

1) The daily AC usage rate was most related to the average daily outdoor temperature compared to the daily maximum outdoor temperature and daily minimum outdoor temperature, in which a logistic regression model with an R² of 0.60 described the relationship between these two variables during the lockdown period;
2) The average daily duration of AC heating was significantly and linearly related to the daily maximum outdoor temperature during the lockdown, compared to the daily mean outdoor temperature and daily minimum outdoor temperature. The linear regression model (R² = 0.90) was used to accurately describe this relationship;
3) Although Wuhan residents had stayed at home for a much longer period of time during the lockdown, the increase in the duration of AC heating usage was not proportional with the increased time at home. The AC usage heating patterns continued to be a part-time intermittent operation during the lockdown period. The increase in AC heating duration time was mainly reflected in the floor standing air conditioners, which are always used in the living room, whilst the greatest increase in duration occurred in the morning (an increase of approximately 1.7 h);
4) After the lockdown, the indoor temperatures that triggered different occupant AC control actions (i.e., turning on, turning off, turning up the set-point temperature, and turning down the set-point temperature) were 1–2 °C higher overall than before the lockdown. This implies that the thermal comfort temperature of occupants has shifted during the lockdown period;
5) During the lockdown, the heating set-point temperature of residents was decreasing compared to its counterpart before the lockdown.

It is well-known that the COVID-19 pandemic has impacted the psychology [47,48,52], and lifestyle [53–55] of many people. Therefore, it is not known where these shifts in AC heating behavior caused by COVID-19 are temporary or permanent; this is worth verifying in a future longitudinal study with a longer timeline.

The lockdown of Wuhan provided an opportunity to examine winter AC heating behavior of residents in the HSCW zone. The results of this study may also point to the current and changing trends in the AC heating behavior of residents within the HSCW zone of China. Thus, these research results may provide empirical data support for research on household energy demand and thermal comfort in China’s HSCW zone.

This research may also provide references for household energy demand and thermal comfort change in the context of a lockdown as a result of the COVID-19 pandemic.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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