The thermal effect of the tandem kang model for rural houses in Northern China: a case study in Tangshan

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ABSTRACT
The kang-stove system (KSS) is a combination cooking and heating system and is the core element of the living space of many rural houses in northern China. The traditional KSS is usually single kang model (SKM) that one stove combines with one kang, which causes inconveniences including an insufficient room heating supply, a small heating range, and subsequent privacy issues for family numbers. Therefore, this paper proposes a tandem kang model (TKM). By combining two kang together and re-organizing the house layout, this model both improves the heat supply effect of the KSS and transforms the kang from a multifunctional space to a relatively mono-functional space to provide more personal space for family members, especially in the winter. To verify the thermal effect of the TKM, CFD simulations were conducted to compare the indoor thermal indexes of a chosen prototype and its modified version with a tandem kang. The results reveal that, compared with the SKM, the TKM exhibits a better thermal performance. It can improve the temperature of the main rooms by 12.7–55.6%. Whereas the form of the TKM should be properly controlled or combined with other assistant facilities to optimize the condition of the uneven surface temperature distribution.

1. Introduction
The kang is a core element of the living space of many rural houses in northern China. It is mainly distributed in 14 provinces (Figure 1), and is widely used in nearly 85% of northern China’s rural houses occupied by 175 million people (Zhuang, Li, and Chen 2009a). Because the winters in northern China winter are very cold, the kang can provide a comfortable microenvironment for residents with a stove to supply heat (Zhuang, Li, and Chen et al. 2009b). People enjoy sitting, sleeping, and having meals on a kang. (Fumihiro 2003) Its theory is similar to that of the hypocaust in Greece (Bansal 1998) and the ondol in Korea (Yeo, Yang, and Kim 2003).

1.1. The kang-stove system (KSS)
The kang-stove system (KSS) is a combination cooking and heating system. Hot smoke from the stove (Figure 2(a)) can pass through the flue of the kang (Figure 2(b)), which is then heated by the smoke and warm the rooms of the home (Li and Yang 2006). The top of the kang is made of thick clay, which endows it with a good heat storage capacity and allows it to continue to radiate heat into the rooms when the stove is not operating.
Moreover, the stove can also be used for cooking. In this way, the heat generated by cooking can be fully utilized to heat the living space. As the core of the KSS, the *kang* is located in the main living space. While its form is slightly different in different regions, the basic model is fairly consistent: a portion of the floor in the room is elevated to form a platform for people to sit on (Figure 3).

In ancient times, because fuels were difficult to acquire, the KSS helped people live through the cold winters with only a small amount of fuel. According to the research by Zhuang (2009), the use of a *kang* for home heating can reduce the building heating load by 50%-80%. Moreover, there is a large amount of straw in Chinese villages; instead of burning it in the field, straw can be burned in stoves to reduce waste (Fan 2016).

However, the *kang* also has some disadvantages; first, it is difficult to heat. Coal, firewood, or straw (Li, Bai, and Ralph 1998) must be continually burned to maintain the stove operation, which is inconvenient, time-consuming, and unhealthy (Ezzati and Kammen 2001). For this reason, many families only keep one *kang* heated. Moreover, because the economic conditions in many villages in northern China are not good, many people do not want to pay for an electricity bill for

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**Figure 1.** The distribution of *kang* in China.

**Figure 2.** Images of a stove and *kang*.

**Figure 3.** The principle of the *kang*. 

1.2. The relative research on the improvement of the KSS

Due to the many shortcomings of the KSS, researchers have proposed some optimization measures. Overall, the optimization of the KSS can be mainly divided into three aspects: improving the structure and form of the KSS itself, combining the KSS with other clean-energy heating facilities, and improving the layout relationship between the kang and the entire house to make the space more suitable for modern life.

1.2.1. Improvement of the KSS structure

There are mainly two kinds of improvements that have been made to the KSS structure: the elevated kang and the hot-wall kang (Wang, Lin, and Su et al. 2012). The elevated kang is characterized by the slight elevation of the bottom of the kang; this changes the heat radiation of the traditional kang from only the top to both the top and the bottom sides, thereby improving its thermal efficiency. (Zhuang, Li, and Chen 2008) Experimental results by Zhuang, Li, and Duanmu et al. (2008) revealed that an elevated kang could maintain the average room temperature 10 °C higher than the outdoor temperature. Li, Li, and Zhen et al. (2017) found that, compared with the traditional kang, the elevated kang reduces the consumption of firewood by 45%. Regarding the hot-wall Kang, its main feature is that a flue space inside the kang is separated as a combustion chamber. During the burning of fuel, the front wall of the hot-wall kang becomes heated, and it therefore exhibits a significantly improved heating effect. (Wang, Lin, and Su et al. 2012) Research by Zhu, Wang, and Lin et al. (2011) revealed that the smoke flow inside the hot-wall kang was more evenly distributed, and the room temperature was increased by 10–20°C. In the research of Li, Gao, and Yang (2016) a new model of a kang flue was proposed to improve both the thermal performance and energy efficiency.

1.2.2. Clean-energy heating facility application

In addition, some researchers have combined the traditional KSS with other clean-energy facilities to improve its heating effect and environmental performance. Yu, Tan, and Zhang et al. (2020); Zhen, Ji, and Guo et al. (2018) combined solar energy with the kang, and its surface temperature could be maintained at 27–38°C at night. Chen, Zhang, and Yang (2006) coupled a passive solar thermal collector wall with the kang, and the results showed that although the initial investment in the solar system was increased by 10%, the operation of this system was significantly better than that of the kang alone; moreover, it could reduce the consumption of coal by about 50% in the winter. Yang, Yu, and Ma et al. (2017) verified that the energy-saving rate of the solar heating system was higher during all-day operation. Research by Li et al. (Gang, Xiaolong, and Shipeng 2014) showed that the average indoor temperature of a solar-assisted kang room was 18.5°C, which was 6.3°C higher than the average indoor temperature when the simple KSS was used. Also, Zhu et al. (Liu, Liu, and Tao 2018) proposed a new type of low-temperature hot-water coil arranged on the surface of the kang; they showed that it could keep 80% of the kang area within a comfortable temperature range. In addition, Zhu, Wang, and Lin et al. (2012) combined the hot-wall kang with a hot-water heating system. They installed a heat collector directly above the stove’s combustion chamber, arranged a radiator in the room, and circulated the hot water inside to transfer the heat in the combustion chamber to the room. The results showed that this facility improved the thermal environment of the room. An experiment by Yu, Wang, and Yang (2015) showed that the hot-wall kang with a hot-water heating system was characterized by an equal temperature distribution, high thermal storage capacity, and better thermal comfort.

1.2.3. Improvement of the layout

Over the decades, some residents have spontaneously adjusted the layout of their houses under the premise of retaining the use of the kang. They have explored the modification of the relationship between the kang and the overall layout of the house to gradually improve the quality of their living environment. According to the research on rural residential space in northeast China by Boda et al. (Boda 2014, “Transformation and Functional Differentiation”) in recent years, some rural residents have split the kitchen space and the laundry space of their houses and adjusted the layout of the living room, thereby transforming the kang from a multifunctional space to a mono-functional space. These transformations have improved the kang-centered living style and two-generation living. 2020 found that, for rural houses in the Manchu village in northeast China, measures such as dividing the main building with a partition wall or lining up multiple main buildings are adopted to
create individual living spaces for each main household. Noguchi et al. (野口孝博, 月舘敏栄, 西村伸也, 等 2003) drew similar conclusions from their rural housing research in Harbin and Shenyang, China.

It can be seen that, regarding the improvement of the KSS, there have been relatively more studies on the structural improvement of the kang and its combination with other new energy facilities, but relatively few studies from the perspective of spatial organization. According to the previously referenced studies, the improvement of the layout of rural houses in northern China has become a spontaneous trend. This phenomenon reveals the necessity of improving the kang in terms of the house layout.

Therefore, this paper proposes a tandem kang model (TKM) from the aspect of the house layout. By combining two kang in series and re-organizing the layout relationship between the kang and the entire house, this model both improves the heating supply effect of the KSS and transforms the kang from a multifunctional space to a relatively monofunctional space to provide more personal space for family members, especially in the winter.

2. Methodology

To verify the thermal performance of the TKM, a prototype of a typical house in Tangshan, Hebei Province was chosen as a case study. Some modifications were made to its layout, and a tandem kang was used to replace the original single kang (Figure 4). A thermal performance comparison between the improved layout with the tandem kang and the original layout with a single kang was then conducted via a computational fluid dynamics (CFD) simulation.

2.1. Case selection

The residences in Tangshan residences primarily have courtyard layouts (Yan and Wang 2018). A single residence typically consists of the main house, front house, wing house, stall, and toilet, of which the main house is the main living space for a family. The gables of the main houses between neighborhoods are adjacent to each other and form a row (Figure 5). The main house is the major area for heat supply in the winter. Hence, this paper primarily discusses the improvement of the main house.

Most main houses have similar characteristics; they are mostly axisymmetric, have three steps, a single floor, and face south. Table 1 presents some common layouts of main houses, all of which have a single kang. In the subsequent analysis, the adopted experimental case is the first layout presented in Table 1. It is the most common layout that exists widely in Tangshan, and other layouts are derived from this basic layout prototype.

![Figure 4. SKM and TKM.](image)

![Figure 5. Image of main houses.](image)
2.2. Case modification

In the chosen case, to properly apply the TKM, some modifications of the layout were made to improve its suitability for the TKM. As illustrated in Figure 6, the lounge of the modified layout was arranged on one side of the house, and two kang rooms were set on the other side and connected. The stove was arranged on the north side, next to the lounge. Moreover, a door was placed in the partition wall between the two kang rooms, and the far kang room was open to the outside, thereby avoiding the disturbance of people staying in one room by other people leaving the house. It must be noted that neither the room distribution mode nor the main dimensions of the original layout were changed in the modified layout. The three-way layout pattern of the original house was inherited. Therefore, the modified layout was still suitable for its original site and coordinated with the surrounding environment.

2.3. Thermal effect comparison

The thermal effect of the TKM was investigated via comparison experiments of the single and tandem kang layouts via CFD simulation with PHENICS software. Two PHENICS models were constructed (Figure 7); the first was the single kang layout model with a total of

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Table 1. Some common layouts of main houses in Tangshan.

| Number | Layout Description                  |
|--------|-------------------------------------|
| 1      | Three-way and one-step layout       |
| 2      | Three-way and two-step layout       |
| 3      | Four-way and one-step layout        |
| 4      | Three-way and north-stove layout    |

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Figure 6. The improved layout of the main house.

Figure 7. Models constructed in PHENICS.

(a) Single kang layout

(b) Tandem kang layout
19,938,959 cells, and the second was the tandem kang layout model with a total of 22,404,740 cells. Regarding the working condition settings, to control the variables, the heating power of the stoves in both models was set to 9000 W under steady-state conditions, and only one stove was considered in each model. Moreover, in the CFD model, all the openings were closed, except for the kitchen door; this is in line with the living habits of native people in the winter when the stove is burning. Finally, according to the climate data of Tangshan sourced from the China Meteorological Administration (http://www.cma.gov.cn/), the air temperature inflow was set to −0.5°C. Moreover, because the heat transfer of air is mainly dependent on the natural convection caused by differences in air temperature, the K-ε model (2000; Nishizawa et al. 2011; Xiangxiang, Rongrong, and Jiaping et al. 2010; 2013) was used for turbulence calculation, and the IMMERSOL model was used for radiation calculation. The main working condition settings are listed in Table 2.

Additionally, the indoor airflow was assumed as follows. The indoor air was assumed to be incompressible and conformed to the Boussinesq equation, which means that the air density only affected the buoyancy. The flow pattern of the indoor air was steady-state turbulence, and the indoor air satisfied the no-slip boundary condition on the inner wall of the room.

### 3. Thermal performance analysis of the TKM

According to previous studies (Lin, Yang, and Wang et al. 2009; Xiemu, Fang, and Guiwen 2014; Li, Li, and Zhen et al. 2017; Huifen, Yuelin, and Guoye et al. 2013), the thermal performance evaluation of kang in the steady state mainly consists of two aspects: the influence on the room temperature and the kang surface temperature distribution. Therefore, four parameters, namely the average room temperature, the standard deviation of the room temperature, the average surface temperature, and the standard deviation of the surface temperature, were chosen as the main evaluation indexes. During the comparison, the naming rules for the rooms were as presented in Figure 8.

#### 3.1. Room temperature analysis

As presented in Table 3 and Figure 9, compared with the single kang layout, the improvement of the temperature of kang room1 in the tandem kang layout was about 12.7%, while that of kang room2 was 55.6%. Additionally, the temperature of the lounge was found to be improved by 27.1%. Hence, with only one stove to supply heat, the TKM can improve the average indoor temperature of the main rooms as compared to the SKM.

Additionally, the standard deviation of the room temperature showed that the room temperature distribution of kang room1 in the tandem kang layout was better than that in the single kang layout, while the temperature distributions of other rooms in the tandem kang layout were slightly higher.

#### 3.2. Surface temperature analysis

Regarding the surface temperature of the kang, because only one stove was heated, the kang in kang room2 in the single kang layout was not considered. As shown in Table 4 and Figure 10, the average surface temperatures of the three kang rooms were similar, among which that of the tandem kang room1 was the highest. This means that tandem kang not only can directly supply heat for one additional room but also has a better heat supply...
effect than a single kang under the same energy consumption condition (one stove used).

According to Figure 11(a1,a2), the path of flue gas from stove to chimney was relatively more direct in the single kang, which may not be conducive to the heat exchange between flue gas and kang. While, according to Figure 11(b1,b2), the path shape of flue gas in the tandem kang was L-shape, which meant a longer distance from stove to

*Table 4. Surface temperature of the kang.*

| Surface temperature | Single kang layout | Tandem kang layout | Tandem kang layout (−3.0 Pa) |
|---------------------|--------------------|--------------------|-----------------------------|
| Highest (°C)        | 32.50              | 42.69              | 20.58                       |
| Lowest (°C)         | 11.29              | 14.85              | 14.37                       |
| Average (°C)        | 18.45              | 20.83              | 17.33                       |
| STDEV               | 5.90               | 9.08               | 1.59                        |

*Figure 9. Temperature fields of rooms.*

*Figure 10. Surface temperature fields of the kang.*

*Figure 11. Ventilation fields of the kang.*
the chimney. Moreover, the length of tandem kang was longer than single kang. Those characters might be beneficial to the heat exchange between flue gas and kang, and made tandem kang has a better heat capacity.

According to the data of the standard deviations (Table 4), the surface temperature distribution of tandem kang1 was not as good as that of a single kang. This phenomenon requires in-depth analysis. According to Table 5, the chimney fluxes of the single kang and tandem kang were similar, while the ventilation rate of the single kang was higher than that of the tandem kang. Also, as presented in Figure 11(a1,b1), that the air velocity in the tandem kang was lower than that in the single kang. That might due to the inner volume of the tandem kang was larger than that of the single kang – Under the similar chimney flux, a larger kang volume reduces the ventilation rate and airflow velocity. A lower ventilation rate and airflow velocity made the heat in the tandem kang easier accumulated at the first half of the kang. That might be the reasons for the uneven surface temperature distribution of the kang. The ventilation rate was calculated by Eq. (1) as follows:

\[ R_v = \frac{F_c}{V} \]  

(1)

where \( R_v \) is the ventilation rate (g/m\(^3\)-s), \( F_c \) is the chimney flux (g/s), and \( V \) is the volume of the kang (m\(^3\)).

Considering the phenomenon of the non-uniform surface temperature distribution of the TKM, in another simulation, a negative pressure (~3.0 Pa) was added to the outlet of the chimney in the tandem kang layout. This negative pressure can be regarded as a smoke evacuator, a simple device that can be installed on the chimney mouth (https://www.amazon.ca/Chimney-Induced-Draft-Evacuator-Fireplace/dp/B07Y2T6P8J). The smoke evacuator can generate negative pressure at the chimney mouth, which can accelerate the flow speed of flue gas and increase the ventilation rate, thereby reducing the non-uniformity of the surface temperature distribution.

The results showed that, with the addition of negative pressure, the ventilation rate was improved (Table 5) and the standard deviation of the tandem kang was successfully reduced with only a slight decrease of the average surface temperature (Table 4). It is also noteworthy that, after the negative pressure was added, the average temperature of tandem kang1 was still higher than that of the single kang. Therefore, the addition of a ventilator on the chimney can help adjust the surface temperature distribution of the kang with only a slight decrease in temperature.

### 4. Discussion of the application of the TKM

In terms of the applicability of the kang, because the residential modes in different regions of China are different, the use of a tandem kang must be adjusted according to the housing types in different regions. However, a positive aspect is that most of the spatial patterns of residences in different regions where kang are widely used follow certain rules. For example, many of the rural houses in the districts that use kang are organized through courtyards. Moreover, the main houses are usually located in the middle of the north side of the courtyard and face south. For a single house, the rooms are similar in size and arranged in a row. These similarities are beneficial to the widespread promotion of the TKM.

It must be noted that the experiment revealed that the volume of the kang and the chimney flux are closely related to the ventilation rate, which is closely correlated with the surface temperature distribution. Therefore, to ensure the thermal effect, the form of the kang should be properly controlled. For example, the volume of the kang should be matched with the wind effect of the chimney, or a smoke evacuator should be added to the chimney when necessary.

In addition, because the KSS uses coal and firewood as the main fuel, it has shortcomings in terms of greenhouse gas production and environmental harm. Hence, the tandem kang is a compromise solution based on traditional habits, economic factors, and thermal comfort factors. It can improve the heating range and heating effect of the traditional KSS in a low-cost manner without increasing the workload or energy consumption, and can reduce the inconveniences of traditional rural houses that are caused by the shortage of heating rooms. However, in future research, combining the TKM with clean-energy systems can be considered.

### 5. Conclusion

Aiming at overcoming the shortcomings of the traditional single kang model (SKM), this article proposed the tandem kang model (TKM) from the perspective of the spatial layout, and the prototype of a typical residence in Tangshan village was taken as a case to verify its thermal effect. Via a limited layout adjustment, the tandem kang was applied to the case house. Then, through CFD simulation, the characteristics of the tandem kang and the improvement of the thermal environment were analyzed.

The following is a summary of the effect of the tandem kang:

| Table 5. Ventilation data of the kang. |
|--------------------------------------|
|                                       |
| Single kang                           |
| Tandem kang                           |
| Tandem kang (−3.0 Pa)                 |
| Chimney flux (g/s)                    | 99.24 | 101.80 | 177.98 |
| Volume of kang (m\(^3\))             | 4.00  | 7.52   | 7.52   |
| Ventilation rate (g/m\(^3\)-s)       | 24.81 | 13.53  | 23.65  |
(1) Under the premise of the use of a single stove, compared with the SKM, the TKM can both improve the heat supply effect of the KSS and transform the kang from a multifunctional space to a relatively mono-functional space to provide more personal space for family members, especially in the winter;
(2) In the chosen case, the tandem kang was found to improve the kang room temperature by 12.7% to 55.6%, which will improve the thermal environment of rooms in the winter;
(3) To ensure that the surface temperature distribution of the tandem kang is within a reasonable scope, its form should be properly controlled or combined with other assistant facilities, e.g., a smoke evacuator.

In conclusion, although there are some shortcomings of the proposed model, the overall effect of the tandem kang is better than that of the single kang. The use of the tandem kang should be accompanied by the consideration of the local conditions and the proper organization of the space according to the characteristics of local houses. Additionally, considering environmental protection, determining how to combine the tandem kang with other clean-energy equipment is worthy of further research.

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