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Uncovering eco-friendly design in the ancient bronze goose-and-fish lamp: an unnoticeable gap boosts ventilation

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The bronze goose-and-fish lamp exhibited in the national museum of China is a 2,000-y-old artifact once used for indoor lighting by nobility in the Western Han dynasty (206 BCE TO 25 CE). The beauty of this national treasure arises from its elegant shape vividly showing a goose catching fish with beautiful colors painted over the whole body. Beyond the artistic and historical value, what enchants people most is the eco-design concept of this oil-burning lamp. It is widely believed that the smoke generated by burning animal oil can flow into the goose belly through its long neck, then be absorbed by prefilled water in the belly, hence mitigating indoor air pollution. Although different mechanistic hypotheses such as natural convection and even the siphon effect have been proposed to qualitatively rationalize the above-claimed pollution mitigation function, due to the absence of a true scientific analysis, the definitive mechanism remains a mystery. By rigorous modeling of the nonisothermal fluid flow coupled with convection-diffusion of pollutant within and out of the lamp, we discover that it is the unnoticeable gap between goose body and lamp tray (i.e., an intrinsic feature of the multicompartmental design) that can offer definitive ventilation in the lamp. The ventilation is facilitated by natural convection due to oil burning. Adequate ventilation plays a key role in enabling pollution mitigation, as it allows pollutant to reach the goose belly, travel over and be absorbed by the water.

artifact | eco-friendly design | multicomponent assembly | natural ventilation | particulate matter emission

The painted goose-and-fish lamp is one of the greatest archaeological discoveries in China, which is highlighted as a cover-page collection by the National Museum of China (1). This bronze artifact was cast during the Western Han dynasty (206 BCE to 25 CE) and was used at that time for indoor lighting by nobility. Cherished by its owner, this extraordinary artwork was buried underground for about 2000 y. Since its discovery in Shanxi Province in 1985, the beauty of this national treasure has attracted tremendous attention from countless visitors. The 53-cm tall lamp vividly shows a long-necked goose turning its head back and holding a fish in its beak (Fig. 1*A*). The whole body is covered by beautiful color paintings and people can clearly see detailed features, including red crown and green feather, etc. The adopted artistic form of water birds catching fish can be traced back to the Yangshao culture in the Neolithic age (5000 BCE to 3000 BCE). In China, goose and fish represent wishes for love and prosperity, respectively. It is also believed that the form of goose catching fish represents desires for success (2).

Beyond the artistic value, technological beauty demonstrated by this lamp is also impressive. People are amazed by the high level of bronze casting technology mastered by the ancient Chinese (3). Moreover, the concept of multicompartmental design for multifunctionality is ingenious. As shown in Fig. 1*B*, the complete lamp, assembled from four components, has three compartments. The lamp tray is a shallow container filled with animal oil for burning. Two curved panels, as lamp shade, are inserted into the groove along the rim of the tray to form the first compartment. The second compartment is the hollow body of the goose with a round hole on its back, where a round protrusion at the bottom surface of the lamp tray can be inserted into. The third compartment is the head of the goose with a long neck on one side and a fish on the other side, which are hollow as well. The neck is connected with the goose body and the top of the lamp shade can fit into the belly of fish. We summarize a number of attractive advantages of this multicomponent and multicompartmental design throughout the life cycle of the bronze lamp. This design allows casting of sophisticated structures using the piece mold technique (3) and facilitates the transportation. Through adjusting the location of two curved panels (i.e., the shade), this ancient lamp offers wind-protection and the control of lighting direction and illumination level (1). Easy cleaning is another attractive feature, since the soot deposited on the inner surface of the lamp can be hardly cleaned without lamp disassembly.

Significance

As one famous environmentally benign oil lamp, the goose-and-fish lamp demonstrates both artistic and technological beauty. It is assembled from three compartments, i.e., lamp tray and shade, goose neck, and goose body filled with water for pollutant absorption. Such multicompartmental design allows for easy cleaning. By simulating momentum, energy, and mass transfer, we discover that the lamp can harness natural ventilation for pollution mitigation, and the small gap between dismountable components is the key for adequate ventilation. This work demonstrates how advanced science and technology can be used to reveal the ancient wisdom hidden in an artifact. The mechanistic findings may inspire optimized design of natural ventilation for sustainable buildings and lead to cost-effective removal technologies for particulate matter emissions.

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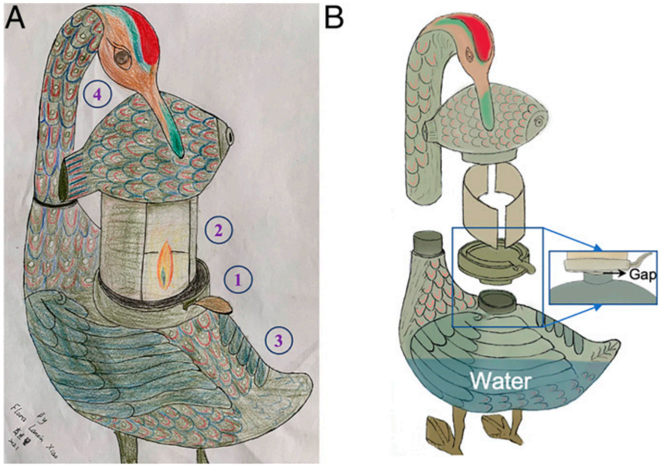

Fig. 1. The bronze goose-and-fish lamp. (*A*) Color painting of the lamp that is in use (image credit: Flora Lanxin Xiao). (*B*) Sketch of the disassembled lamp. The complete lamp, assembled from four dismountable components, has three compartments. The first compartment consists of the lamp tray (*1*) and the lamp shade (*2*). The second compartment is the goose body (*3*). The third compartment is the goose head together with the neck and fish (*4*). Before assembling the lamp, water can be prefilled into the goose belly through the hole on the back of the goose body.

In addition to the merits listed above, what amazed people most is the environmentally friendly design concept demonstrated by this artifact. It is widely believed that when the lamp was used for lighting 2,000 y ago, the goose belly was filled with water and the long neck served as a duct for the smoke generated by burning plant oil, animal fat, or wax (4). Rather than polluting the indoor air, the smoke flowed into the belly through the neck and was finally absorbed by the water. This claim together with its explanation can be identified in numerous reports on newspapers and museum websites (5, 6), which sounds reasonable and has been taken for granted by most people.

As chemical engineers, two critical questions came into our mind: (1) how can smoke flow into the goose belly that is below the flame? and (2) how effective this eco-design is? The first fundamental question should be explored scientifically to uncover the underlying pollution mitigation mechanism. Pursuing the answer to the second question will offer us quantitative understanding and may lead to improved designs. Since its discovery, however, no one has ever quantitatively evaluated the effectiveness of this design in mitigating indoor air pollution. According to a study on cultural relics (7), there are only six goose-and-fish lamps unearthed. Carrying out experiments on these invaluable national treasures is almost impossible. There are very few papers (mostly in Chinese) attempting to address the first question, whose authors include researchers in archaeology, art, history, and philosophy. They proposed some hypotheses including natural convection (8, 9) and siphonage (10), which however, are highly questionable without rigorous data support and scientific analyses. Buoyancy-induced natural convection cannot explain the downward flow from the top of the neck to the belly of the goose. The idea of drawing an analogy between the goose neck and a siphon is scientifically incorrect since in this specific system the fluid flowing through the goose neck is not liquid (11).

Application of cutting-edge technologies and advanced theories to the study of cultural heritage is a rapidly evolving frontier (12, 13). Artificial intelligence was used by a team of electrical engineers and mathematicians to separate X-ray images of the *Ghent Altarpiece* (14). A statistical mechanics approach was applied by a physicist to the study of the structure of musical harmony (15). Physicists and chemists worked together to uncover modern paint forgeries by radiocarbon dating (16). The ongoing excavation of the legendary Sanxingdui Ruins site in southwest China is a joint effort by experts from 34 universities and research institutes, even including some firefighters. The above-listed successful examples demonstrate the power of interdisciplinary collaboration for making breakthrough in this promising area. We, as chemical engineers with expertise in multiphysics modeling and simulation (17, 18), decided to decode the riddle in this ancient lamp by resorting to in silico experiments and theories of transport phenomena.

Results

Smoke particles are released from the flame into the air; some of them will be contained in the lamp, while others will leak into the room. Those particles contained in the lamp have three destinies: remain in the hollow compartments, be absorbed by the water prefilled in the belly, and be deposited on the inner surface. Since the lamp is not a closed system, it is reasonable to assume a constant concentration of smoke in lamp compartments once reaching a steady state. Thus, at the steady state, to ensure mass conservation in the gas domain of the lamp, continuously generated smoke particles from the source (i.e., the flame) should be consumed by three sinks: leakage from the lamp to the room, absorption by the water, and deposition on the inner surface of the lamp. The last sink term was neglected in mass conservation calculation, since the deposition rate was estimated to be much smaller than the leakage rate and the absorption rate (*SI Appendix*). Consequently, in order to evaluate the effectiveness of the eco-design, we defined a protection efficiency that is the ratio between the absorption rate and the release rate of smoke particles. A 100% protection efficiency refers to the ideal case of zero leakage, i.e., all smoke particles are contained in the lamp.

Surprising Results from an In silico Experiment. Interested in revealing quantitatively the protection efficiency of the lamp, we performed an in silico experiment. The lamp was placed in the middle of a room with an ambient temperature of 20 °C. Fresh air flowed into the room at a constant velocity of 0.1 m/s. The geometry of the lamp was constructed based on the one in the National Museum of China. The belly of the goose was half-filled with water. The shade was 25% open, facing the wind (*SI Appendix*, Fig. S1*A*). The flame continuously released smoke particles at a constant flux of 4.99×10^{-12} mol/($m^2 \cdot s$). We developed a comprehensive multiphysics model to simulate momentum, heat and mass transport phenomena in this system (see *Materials and Methods*). It was found that, surprisingly, the protection efficiency was 0.08% only, i.e., 99.92% of smoke released from the flame leaked into the room and the amount absorbed by the water was almost negligible. In other words, the lamp can hardly mitigate indoor air pollution.

We took a close look at what happened in the system to understand the counter intuitive results. Fresh air flowed into the lamp through the opening of the shade. The burning flame with a constant outer surface temperature of 950 K (676.85 °C) heated up the surrounding air (Fig. 2*A*). The temperature of the bronze lamp was increased to 42.2 °C due to hot air and radiative heating (Fig. 2*B*). The temperature difference in the air domain led to air density difference and as expected, buoyancy driven natural convection can be observed (Fig. 2 *C* and *D*). The hot air adjacent to the flame carrying smoke particles rose to the fish cavity, where part of the air streams went further up to the top of the neck while others returned back to form

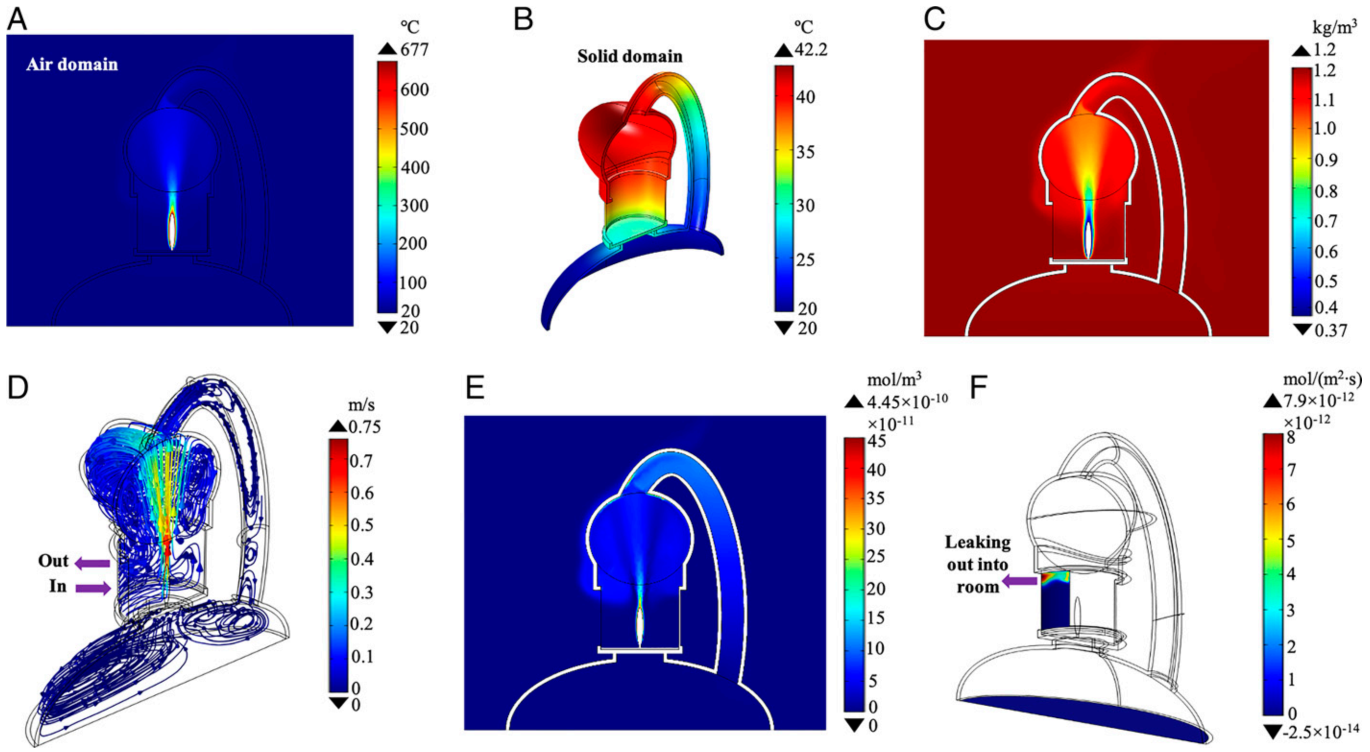

Fig. 2. Steady-state results of the in silico experiment. (*A*) The temperature distribution in the air domain (a cross section view). (*B*) The temperature distribution in the solid domain (a 3D view), i.e., the bronze lamp. (*C*) Air density distribution. (*D*) Streamlines of the airflow with arrows showing the direction of flow. (*E*) Smoke concentration distribution. (*F*) The distributions of normal flux of smoke on the opening of the shade and the water surface. The direction of the flux is indicated by its value. A positive value indicates an outward flux, i.e., in this specific case, pointing out of the lamp or into the water.

vortexes in the fish cavity. The air streams reaching the top of the neck, however, did not have sufficient momentum to flow downward to arrive at the belly of the goose. Instead, halfway down the neck, they returned back to the top of the neck (see the velocity field in Fig. 2*D*). As a result, after flowing into the lamp, the fresh air could hardly reach the goose belly through the long neck. Instead, part of the air flowed back into the room through the opening. In this specific system, the Peclet number is about 1,423 (see *Materials and Methods*), which is much larger than 1 indicating an advection dominant mass transfer process. Consequently, the concentration of smoke in the goose belly was much lower than that in the fish cavity (Fig. 2*E*). Furthermore, the absorption flux of smoke particles on the water surface was almost negligible as compared with the flux leaking from the top part of the opening (see Fig. 2*F*), although smoke particles were assumed to be absorbed completely and instantaneously once reaching the water surface.

An Unnoticeable Gap for Significant Ventilation. We then had to decide whether the pollution mitigation function of this ancient lamp believed by most people is just an unrealistic expectation or there is something wrong with our in silico experiment. In order to realize pollution mitigation, smoke particles carried by the air have to travel along the long neck of the goose and reach the water surface beneath the flame. In other words, the fresh air flowing into the lamp through the opening has to distribute well in all three interconnected compartments of the lamp, which is not the case in Fig. 2. This observation inspired us to think about the strategy for harnessing natural ventilation in the architectural design. Ventilation moves the fresh air into a building or a room, and distributes the air within the space. It is known that single-sided ventilation with the space otherwise sealed hermetically may not offer sufficient air changes, and multiple openings should be designed properly in order to deliver the external air to each part of the space in an efficient manner (19). The lamp's geometry constructed so far for the in silico experiment is like a space with single-sided ventilation because there is only one opening for air exchange, which led to poor air distribution in the space (Fig. 2*D*). We revisited carefully the design of multicomponent assembly in Fig. 1 with a hope to identify the key element we may have missed. It was reported that the lamp tray inserted into the goose body can be freely rotated all around to adjust the lighting direction, which implies that the connection between them cannot be seamless. Similar to the gap between mortise and tenon in traditional Chinese timber structures that offers superior seismic performance, the gap here may play an unexpected role in indoor air pollution mitigation. We hypothesized that the unnoticeable gap between lamp tray and goose body (Fig. 1*B*), served as the second opening, can significantly improve the protection efficiency of the lamp.

To test the hypothesis, a 2-mm gap was placed between the lamp tray and the goose body (see the comparison of two lamp geometries in *SI Appendix*, Fig. S1*B*) and the simulation was carried out again with all other conditions unchanged. Flow patterns in the lamp was drastically changed due to the introduction of this small gap. The air flowed unidirectionally into the goose belly through the neck, which led to a much better air distribution in the compartments (see the comparison between Figs. 2*D* and 3*A*), i.e., a better ventilation. The ventilation rate was increased by more than 30% (from 2.18×10^{-4} kg/s to 2.86×10^{-4} kg/s). Quantification methods are given in the section of *Materials and Methods*. Downward flux of smoke could be observed in the neck (Fig. 3*B*), which offered a higher concentration of smoke in the goose belly (see the comparison between Figs. 2*E* and 3*C*). As a result, the rate of smoke absorbed by the water was increased from 3.92×10^{-18} mol/s to 8.22×10^{-16} mol/s. Hence, the protection efficiency was indeed significantly improved from 0.08%

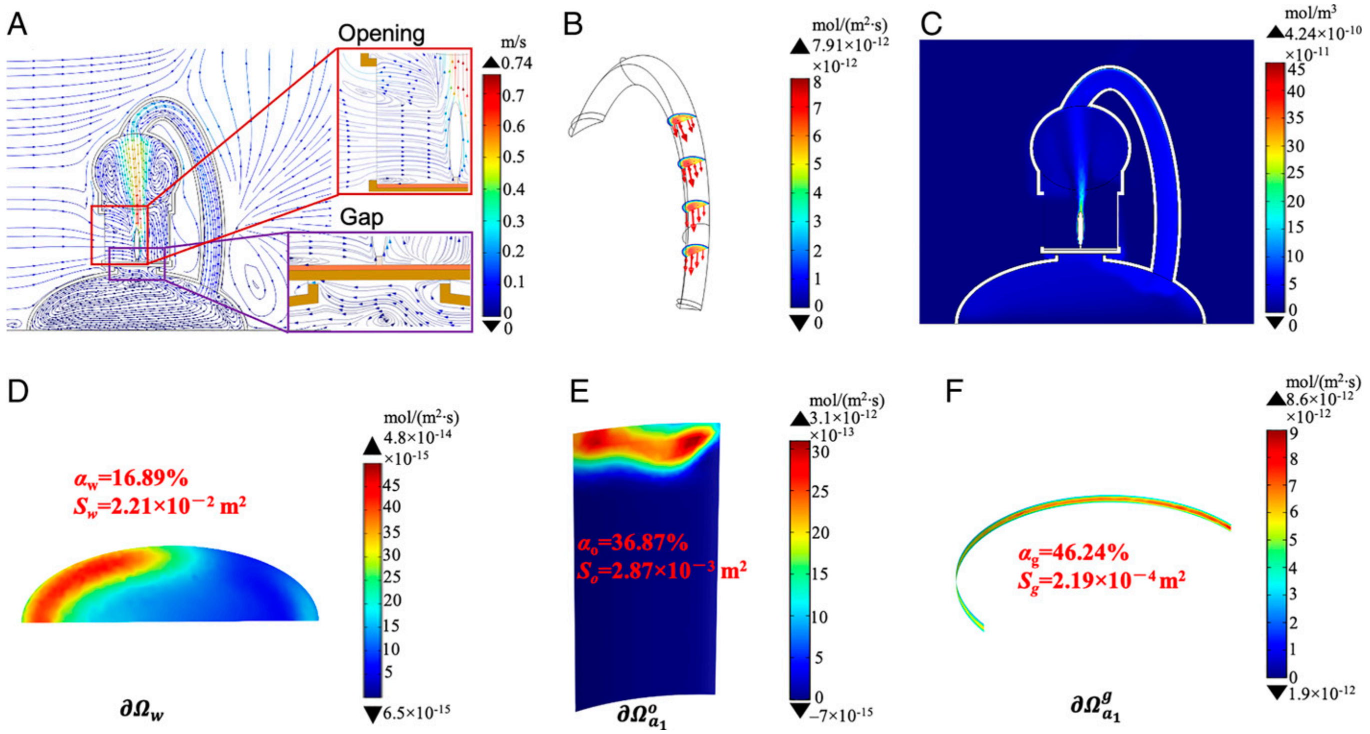

Fig. 3. Steady-state simulation results for the lamp with a 2-mm gap between lamp tray and goose body. (*A*) A cross-section view of streamlines of the airflow with arrows showing the direction of flow. The color bar indicates the velocity magnitude. Two *Insets* enlarge air exchange patterns at the opening and the gap respectively. In order to quickly identify the location and clearly see the airflow in two *Insets*, the bronze body and fuel are colored in brown and orange respectively. (*B*) A 3D view of airflow along the neck and the distributions of normal flux of smoke at four cross sections. The length of the red arrow is proportional to the magnitude of air velocity. (*C*) Smoke concentration distribution. (*D*–*F*) show the distributions of normal flux of smoke on the water surface, the opening and the gap respectively. The direction of the flux is indicated by its value. A positive value indicates an outward flux, i.e., in this specific case, pointing out of the lamp or into the water.

to 16.89% (Fig. 3*D*), i.e., ∼210 times higher. As shown in Fig. 3 *A*, *E*, and *F*, the other 83.11% of smoke leaked into the room through the upper part of the opening and the gap. It is interesting to note that the majority of smoke leaked through the small gap rather than the opening, although the gap is 13 times smaller in size, evidenced by the highest flux of smoke on the gap surface (Fig. 3*F*).

Discussion

The piece mold technique was used to cast the bronze lamps. Even for the same experienced craftsman, it is understandable that he/she can hardly make two identical clay molds. As a result, every bronze artifact is unique. The gap size should be different for different goose-and-fish lamps. The Shanxi Museum in China took advantage of 3D scanning to demonstrate a real goose-and-fish lamp (20). We identified the gap between the lamp tray and the lamp body in the 3D image, whose size can be estimated based on the proportion in geometry. For that specific lamp, the gap thickness is ∼2.1 mm, which is close to the value of 2 mm adopted for the base case study. Since the gap plays a key role in promoting ventilation, additional gap thickness (δ) values were further explored, which include 0.5 mm, 1.0 mm, 1.5 mm, 2.5 mm, 3.0 mm, 3.5 mm, 4.0 mm, 4.5 mm, and 5.0 mm. Increasing gap size from 0 mm to 1 mm leads to a drastic increase of average smoke flux on the gap surface (see violet dots in Fig. 4*A*), which becomes much higher than the average flux on the opening and the water surface. Noticeable reduction of average flux can be identified for the opening (see blue diamonds in Fig. 4*A*). A 25% open shade ($\varphi=1/4$) gives an opening area of 2.87×10^{-3} m^2, which is ∼25 times larger than that of a 1-mm gap. The leakage rate from the opening is still larger than that from the gap (see Fig. 4*B*). Further enlarging the gap from 1 mm yields reduction of average fluxes on both opening and gap. The leakage rate from the opening decreases accordingly. However, continuous increase of leakage rate from the gap can be observed, which is due to the increase of the gap size. For the cases with a gap lager than 2 mm, the majority of smoke leaks from the gap into the room, rather than from the opening (Fig. 4*B*). The introduction of the gap allows air carrying smoke particles flow from the flame to the goose belly through the long neck (Fig. 3*A*). The increase of gap size boosts ventilation in the lamp (see the red dots in Fig. 4*C*), offering more smoke particles reaching the water surface. Although only slight increase of average absorption flux of smoke on the water surface can be observed (Fig. 4*A*), the increase of the absorption rate or the protection efficiency with the increase of gap size is significant (see red squares in Fig. 4*B*). This is because the lamp was designed to have a plump belly, which offers a high surface area of water for absorption (see the comparison of surface areas S_w, S_o, and S_g in Fig. 3 *D*–*F*). The protection efficiency of a 3.5-mm gap system is 18.96%, which is 237 times larger than the system without a gap. Further increase of the gap size from 3.5 mm to 5.0 mm leads to a moderate increase of the ventilation rate and a moderate reduction of the smoke concentration in the lamp (Fig. 4*C*). The enhancement of the protection efficiency, however, is insignificant (from 18.96% at 3.5 mm to 20.13% at 5.0 mm, see the red squares in Fig. 4*B*). When the gap size exceeds 3.5 mm, leakage rates from the gap and the opening reach a plateau. It tells us, at 25% opening of the shade, the increase of the gap size beyond 3.5 mm has almost negligible influence on the protection efficiency. Moreover, a better ventilation yields a lower average concentration of smoke in the

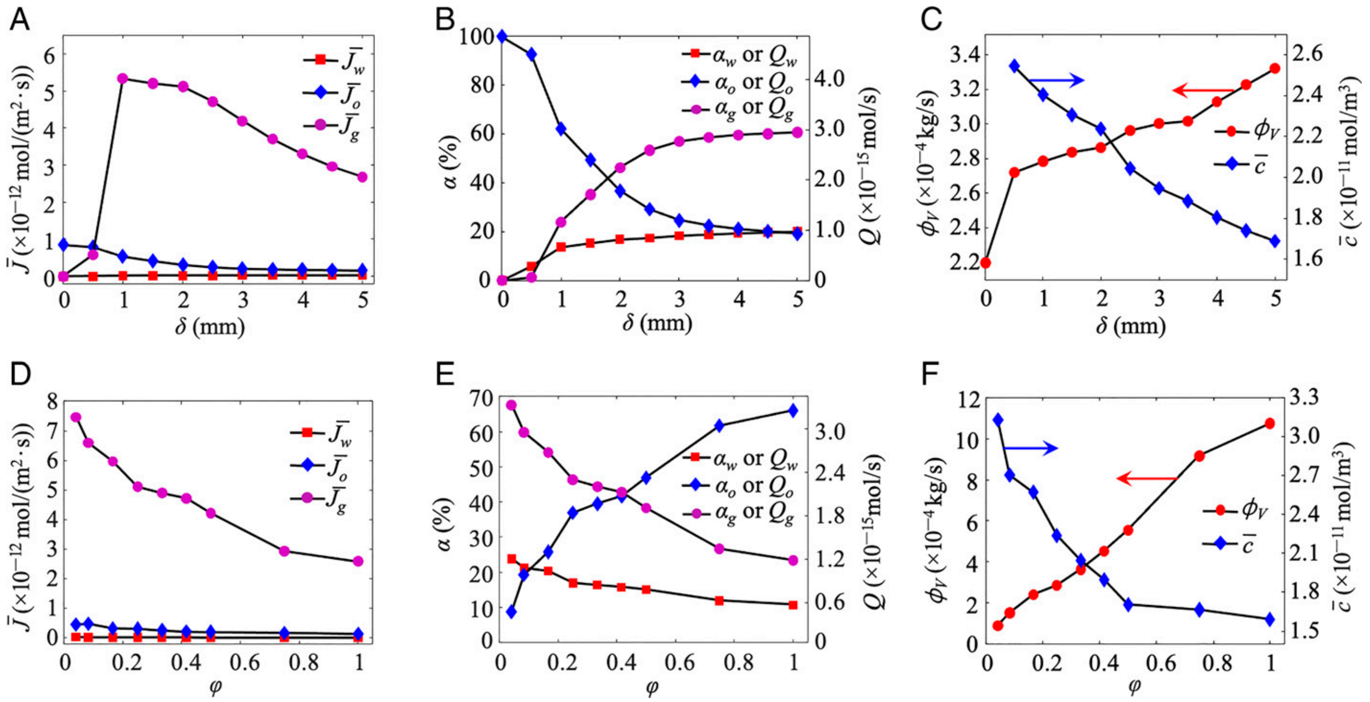

Fig. 4. The influence of the gap thickness δ and the opening size φ on: (*A*, *D*) the average smoke flux on the water, opening and gap surfaces, (*B*, *E*) the absorption rate of smoke on the water surface, and leakage rates through the opening and the gap, as well as their proportions, and (*C*, *F*) the ventilation rate and the average smoke concentration in the lamp. The opening size is 1/4 for (*A*–*C*). The gap size is 2 mm for (*D*–*F*).

lamp (Fig. 4*C*), which is preferable from cleaning point of view. Long-term use of the lamp will inevitably lead to the accumulation of smoke particles deposited on the inner surface of the lamp, and a lower smoke concentration indicates a less severe accumulation.

The air inside the lamp exchanges freely with the air outside through two interfaces, i.e., the gap $\partial\Omega_{a_1}^{g}$ and the opening $\partial\Omega_{a_1}^{o}$. The size of the gap is almost fixed for a specific lamp, while the opening size can be adjusted by rotating the two panels of the shade (Fig. 1). The influence of a set of opening sizes (i.e., φ =1/24, 1/12, 2/12, 3/12, 4/12, 5/12, 6/12, 9/12, and 1) on protection efficiency was investigated. The lamp without a shade corresponds to the case with a 100% open shade (φ=1). Enlarging the opening size leads to a higher ventilation rate and a lower average smoke concentration in the lamp (Fig. 4*F*). However, in this scenario, a better ventilation yields a decline of protection efficiency (see the red squares in Fig. 4*E*). It is because the leakage of smoke from the opening becomes more significant with the increase of the opening size (see blue diamonds in Fig. 4*E*), although the average flux on the opening surface is slightly decreased with the increase of the opening size (see blue diamonds in Fig. 4*D*). These findings tell us the environmental protection performance of this lamp is not a simple monotonic function of the ventilation rate. A shade-missing lamp can offer 10.69% protection only. The smallest opening (i.e., φ =1/24) offers the best protection, i.e., 23.76%, which is slightly higher than 20%. Note that an opening size of 1/24 may not be sufficient from indoor lighting point of view. One can adjust the opening size to pursue a decent balance between the illumination level and the pollution mitigation performance.

We are now able to answer the two questions raised in the introduction part of this paper. The secret for the downward flow of smoke in the lamp lies in the ingenious ventilation design of the lamp. More than 2,000 y ago, the designer creatively took advantage of an unnoticeable gap between the lamp tray and the goose belly (that is actually an intrinsic feature of the multicomponent design) as a second opening to harness natural ventilation in the lamp. This gap, although very small, allows the inflow air from the opening of the shade together with smoke particles flow downward into the goose belly through the long neck, and further get out of the lamp from the gap. The establishment of this passage is the key for enabling lamp's environmental protection function, since the water surface for absorption is on this route traveled by most smoke particles. We discovered that the introduction of the gap can boost the absorption rate by more than 200 times. The ventilation is facilitated by natural convection. Simulations were performed to illustrate potentially even better designs for the claimed practical purpose. Results show that the sizes of the gap and the opening influence ventilation and hence the protection efficiency. Under the conditions we investigated, a lamp with a larger gap and a smaller opening offers a better protection. The maximum protection efficiency can reach around 20% (Fig. 4 *B* and *E*).

We note that two assumptions adopted in this work affect prediction precision, which can be addressed in the future. The first one is the neglect of particle deposition on the wall. Precise prediction of the deposition rate of smoke particles on the inner surface of the lamp is a very challenging task. It is understandable that the local deposition flux is affected by many factors including the physical and chemical properties of particles and surfaces and the local environment (e.g., local smoke concentration, flow velocity, and humidity). In the future, once we have a reliable model for the local deposition flux, which may be a function of the local smoke concentration, local shear stress, and even particle size distribution, we can integrate that deposition model into the current multiphysics model as a mass-transfer boundary condition on the bronze wall. In this way, the release rate Q_f becomes the summation of four parts, i.e., the leakage rate from the opening Q_o, the leakage rate from the gap Q_g, the absorption rate Q_w, and the deposition rate on the bronze wall Q_b. In addition to the three ratios quantified so far, α_o, α_g, and α_w, we will have the fourth ratio α_b. The protection efficiency becomes the addition of α_w and α_b, since smoke particles absorbed by the water and deposited on the lamp surface are contained in the lamp. From this point of view, we may have slightly underestimated the protection efficiency by neglecting particle deposition on the wall. The second assumption is the instantaneous absorption of smoke by water. Water has been conventionally used for effective removal of particulate matter in air. The goose body was designed to have a plump belly and lamp users could regularly replace water in the belly, which can offer a large volume of frequently replaced fresh water to ensure a low concentration of smoke particles in the water. Considering these factors, the simplified approach adopted here for absorption flux quantification is reasonable. This simplification is essentially the best-case scenario, which offers an upper bound of the absorption flux. From this point of view, we may have slightly overestimated the protection efficiency by neglecting mass transfer resistance in the liquid phase.

Our current work developed a generic multiphysics model and associated analysis methods for the investigation of protection efficiency of almost all anti-pollution bronze lamps in the Han Dynasty, including ox-shaped, phoenix-shaped, and stove-shaped lamps and the lamp of Changxin Palace. We revealed the anti-pollution mechanisms shared by all those lamps. The lamp is a cleverly designed natural ventilation system, whose ventilation rate can be adjusted as needed. By resorting to this design, air can be distributed well within the lamp and its exchange with the outside fresh air is effective. It may inspire the design of optimized natural ventilation systems with many applications. For instance, sustainable buildings today ask for the cost-effective natural ventilation design that can offer fresh air for building occupants and lead to significant energy savings at the same time. The World Health Organization (WHO) has been promoting natural ventilation design for infection control in health-care settings (19). In addition to harnessing natural ventilation for airflow control and hence particle trajectory control, the lamp takes advantage of water for smoke particle absorption to mitigate indoor air pollution. This synergistic strategy to use both wind and water for air pollution control may inspire rational design of cost-effective removal technologies for particulate matter emissions that can be used in homes, restaurants, party rooms, and smoking rooms, etc. Moreover, the design concept imparted by ancient Chinese craftsmen to this 2,000-y-old artifact will motivate designers today to practice sustainable design of multifunctional products featuring both artistic and technological beauty.

Materials and Methods

To carry out in silico experiments, we constructed a 3D geometry with a lamp in the middle of a room. Detailed geometries are illustrated in the *SI Appendix*. With natural convection taken into account, the nonisothermal flow of air inside and outside of the lamp is modeled using compressible Navier-Stokes equations coupled with a convective and conductive heat transfer model. Radiative heat transfer is also modeled to heat up the bronze body of the lamp. Smoke particles' Stokes number in this work is less than 1.38×10^{-4} (*SI Appendix*), which is much less than 1. It means that the time it takes a particle to respond to the changes in the flow is much shorter than the smallest time scale of the flow. Hence, particles follow fluid streamlines closely. Smoke particles released from the flame are thus modeled as diluted species in the air. The transport of smoke particles is governed by a diffusion-convection model. It is assumed that smoke particles, once reaching the water surface, can be instantaneously absorbed and removed away from the gas-water interface. All governing equations together with boundary and initial conditions can be found in the *SI Appendix*. The coupled governing equations were solved at steady state using COMSOL Multiphysics (21) and a mesh independence study was conducted to identify an appropriate meshing scenario.

To analyze and understand the environmental protection function of the lamp, we defined the protection efficiency, the ventilation rate and the average smoke concentration in the lamp. Detailed calculation formula together with quantification methods for the Reynolds number, Peclet number, and Stokes number can be found in the *SI Appendix*.

Data Availability. All study data are included in the article and/or supporting information.

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