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Conservation-Focused Climate Control System for an 18th Century House Museum in the Forbidden City, China

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SUMMARY

A minimally intrusive and conservation-focused climate control strategy was developed and successfully implemented in Juanqinzhai, an 18th century building located in the Forbidden City, China. The building envelope was air-tightened to significantly reduce the infiltration of outside air, and large glass windows were double-glazed to improve thermal insulation. A mechanical system installed in the attic was designed primarily to limit relative humidity to less than 55% for conservation of the historic interior, using dehumidification while allowing for variations of temperature. The combination of air-tightening the building envelope and operation of the high performance filter system now successfully controls the dust problem. This climate control strategy has successfully reduced the annual variation of relative humidity from 90% to only 15% and has completely eliminated the spatial variation of the climate. The system has maintained the intended conservation climate of 40-55% relative humidity in the building during its first year of operation.

INTRODUCTION

There is great reluctance to introducing a mechanical climate control system into historic buildings, since it may require significant amounts of alterations to both the building's fabric and structure for its installation. There is also concern that the potential is high for unintended impacts on the building and its interior when significant changes may occur in the environment to which the materials have been acclimatized over centuries. For these reasons, it makes sense to just rely on the building's original passive features or adapt original heating and ventilation methods; however, those controls were designed for primarily occupant comfort and often do not provide the necessary preservation environment for the building, its interior, and its collections. Even if ventilation may have worked in the past, unfiltered ventilation or open window ventilation can often result in the serious intrusion of dusty polluted air and insect infestation. A sensibly designed mechanical system can be installed with minimum alterations to original fabrics of the historic building and provide excellent environmental protection to both the building and collections, and at the same time provide reasonable comfort for occupants and visitors [1, 2].

The Qianlong Emperor (rained from 1735 to 1796), the 4th emperor of the Qing Dynasty (from 1644 to 1912), was a well-known patron of arts and crafts. He ordered the construction of Qianlong Garden (1771- 1776); this retirement complex of palaces and gardens consists of 27 structures in the northeast section of the Forbidden City. Among them is Juanqinzhai (224

m^2 floor area and 1200 m^3 volume), or the Studio of Exhaustion from Diligent Service, a unique building due to the quality and diversity of arts and crafts used in its construction, decoration and furnishings. The relatively simple structure, aligned east–west, was built with the traditional method of post and beam assembly with masonry infill and limited architectural features. Its interior, however, is rich and divided into two halves, reception rooms and a private theatrical performance area, and they have unique decorative schemes and features. The reception area contains polished iron wood used in their framing; casement windows covered with double-sided embroidered silk; geometric pattern surface decoration in extruded bamboo thread marquetry with carved jade insets; and naturalistic scenes carved in low relief and covered with bamboo veneers. In addition, rooms have landscape paintings and works of calligraphy mounted directly on the wallpapered walls. The theater side contains a roofed stage with a dramatic two-story viewing area, mural paintings on silk which cover entire walls and ceiling, and wooden surfaces painted to resemble a special bamboo. It also contains unique and exquisite silk *trompe l'oeil* paintings on the ceiling and walls. After the decline of the Qing Empire, the building was abandoned and its interior elements were left exposed to the elements.

The restoration of the Qianlong Gardens, which is expected to span more than a decade, began in 2002. Juanqinzhai was selected as the first pavilion for the restoration project to develop methodologies to be used in other buildings in the garden complex. The condition assessment of the building and its interior performed by Mecklenburg and Liu [3] indicated large relative humidity variation as the major cause of deterioration and recommended an environment of 30-65% RH to limit hygroscopic dilatations of materials used in the building with a winter minimum temperature of 10˚C to maintain their ductility. The installation of a mechanical climate control system was decided to demonstrate the system as a model that can be used in other buildings in the garden. This article describes the concept development, installation, and operation of the conservation-focused climate control system in Juanqinzhai.

METHODS

Analysis of historical weather data of the previous 21 years in Beijing [4] has shown that the capital city has four seasons: spring, summer, fall, and winter. It has three cold and dry winter months: December, January, and February (average temperatures of -1˚C, -3˚C, and 0˚C and average dew point temperatures -12˚C, -16˚C, and -13˚C, respectively); and three hot and humid summer months: June, July and August (average temperatures 24˚C, 26˚C, and 25˚C and average dew point temperatures 15˚C, 20˚C, and 20˚C, respectively), when 74% of annual total rainfall, 576.9 mm, were recorded. Spring and fall have been gradual transition periods between winter and summer. The outdoor temperature fell to -17˚C in January and reached 41˚C in August. This large annual climate variation provides a major challenge to preserving both the building and collections in Juanqinzhai.

In Beijing, high concentrations of airborne particulates and gaseous pollutants are also problematic. The source of particulates is primarily fine abrasive sands brought in by desert winds. Combustion of fossil fuels from automobiles and commercial vehicles, as well as domestic uses, produces fine but abrasive dust and ash that also contributes to airborne particulates found in the city. Yu [5] reported particulate levels of 296.6 $\mu g\ m^{-3}$ in winter and 259.9 $\mu g\ m^{-3}$ in summer. The World Health Organization [6] has reported sulfur dioxide levels of 90 $\mu g\ m^{-3}$ and nitrogen dioxide levels of 122 $\mu g\ m^{-3}$ in Beijing. Beijing and Mexico City are listed as the most polluted cities in the world, with high levels of suspended particles, sulfur dioxide and nitrogen dioxide.

Hourly temperature and relative humidity data collected by Tsinghua University at the middle of Juanqinzhai between March 4 and December 23, 2005 are plotted on a psychrometic chart in Figure 1. The highest temperature was 28.5˚C in July, and the most humid condition of 92% RH at 27.5˚C was recorded in August. The driest and the coldest were 12% RH and -2.5˚C, respectively, both in December. (January and February data were missing.) Our spot measurements showed that the temperature varied more than 2˚C throughout the building interior, as the air tended to be stagnant in the building due to its long length and many interior walls. Temperature inside Juanqinzhai closely tracked that of the outside. However, the interior temperature was more stable than the outside with typical daily variations of less than 2˚C throughout the year. Relative humidity in the building also tracked outside conditions, with less daily and day-to-day variations. The majority of relative humidity higher than 70%, which can activate fungi, was recorded when the temperature reached higher than 20˚C. Sustained RH values of 75-85% were recorded in July and August, and less than 25% RH at subzero temperature conditions were logged in December.

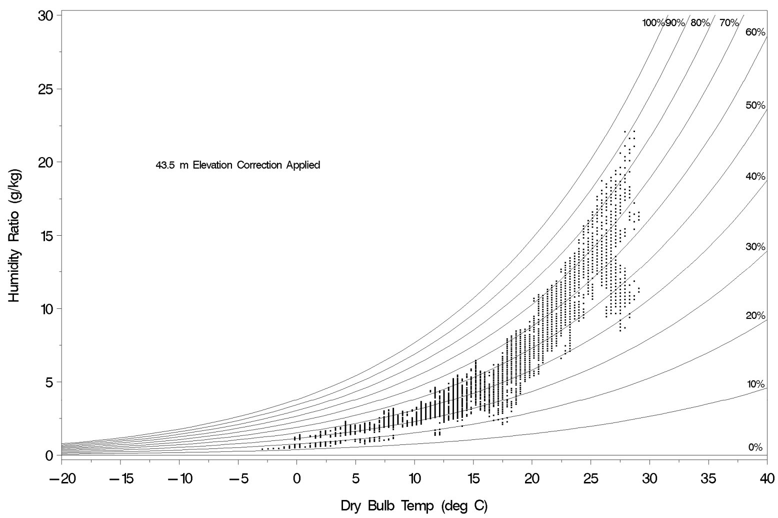

Figure 1 Hourly temperature and relative humidity data at the middle of Juanqinzhai plotted on a psychrometic chart. (Data between March 4, 2005 and December 23, 2005, collected by Tsinghua University)

We proposed the implementation of an integrated climate improvement strategy combining minor modifications to the building envelope, the installation of a minimally intrusive mechanical system, and conservation-focused visitation operation. The objectives are to maintain the preservation environment for the historic collections and interiors of Juanqinzhai as well as the building itself. The strategy focuses on reducing daily and seasonal variations of both temperature and relative humidity by limiting both extremes and alleviating the following conditions. Special focus was given to:

- Preventing high levels of relative humidity that pose a risk of fungal damages.
- Preventing low levels of relative humidity that pose a risk of mechanical damages.
- No humidification to avoid a risk of condensation, therefore no heating in winter.
- Limiting airborne dusts.
- Creating primarily a preservation environment for the collection, visitor comfort is a secondary consideration.

Other restrictions were that it should be modest in scale, simple and inexpensive to install, monitor and maintain.

The following specifications were developed and forwarded to a local HVAC contractor for the engineering design and installation.

MECHANICAL

The mechanical equipment should consist of an air handler, supplemental condenser, ducts, sound attenuation, and computerized controls. The air handler should contain a 10% pre-filter, 30% intermediate filter, and a HEPA box final filter. Downstream of the filters there should be a direct expansion (DX) cooling coil, DX hot gas heating coil, and fan. Downstream of this there should be a reserved compartment section for a future additional heating coil and humidifier. The air handler should also contain the DX compressor within the air handler. The air handler should be able to circulate 7200 m^3/hour of air with sufficient power to overcome the resistance of its filter system, cooling and heating coils, connected supply and return ducts, sound attenuators and fittings. The design inlet conditions to the cooling coil should be 27˚C at 55% RH. The hot gas-heating coil should utilize the refrigerant hot gas to reheat the air steam as needed to maintain the space RH at its set point. Maximum velocities within the air handler should not exceed 2.5 meter/sec. A supplemental condensing unit should be located at the west exterior side of the building to reject heat as needed to prevent overheating of the discharge air steam into the space. All refrigerant lines should be run exterior of the building so as to avoid placement over the west attic space.

Ducts should be connected to the air handler and terminate with distribution grills at the machinery space enclosures penetration points. The grills should be sized for low velocity and concealed vertically from view. The ducts should contain sound attenuators at each connection point to the air handlers along with a separating flexible boot.

ELECTRICAL

An electrical service connection, service switch, distribution panel, remote on/off/auto control, local wiring in conduit, local disconnects, and air handler wiring should be provided. Their sizes should be in accordance with local codes and capable of safely operating the air handler and its controls under all conditions. There should also be a smoke detector located in the air handler which should shut down the air handler in case of smoke and capable of sending an alarm signal to the fire alarm system.

PLUMBING

There should be a spill pan of waterproof construction located under the entire air handler, its refrigerant lines and condensate drain line to collect unwanted water. It should contain a water spill alarm connected to the control system. A condensate drain line should be connected to the air handler to drain its condensate through a trapped copper tubing system by gravity to the northern drain at the building exterior.

MONITORING AND CONTROL

The air handler should be controlled by highly accurate sensors located in the supply and return ducts. The computerized controls should be installed locally in the machinery space and remotely in a space to be determined by the Palace Museum. The climate control system should have the ability to monitor the climate at several locations (inside the air handler, inside and outside the building) and to store the data for a fixed length of time for periodic data downloading to a PC. It should have remote monitoring as well as Internet control capability. Other buildings in the Qianlong Garden will be climatized in the future. This means that the system should be networkable and accessible through both the network of Palace Museum and the Internet.

SEQUENCE OF OPERATION
A sequence of operation described in Figure 2 was proposed for the operation of the mechanical system. In winter conditions (below 15˚C outside), the fan should run continuously while the dehumidification mode is turned off. In spring and fall conditions (above 15˚C but below 27˚C outside), the dehumidification mode is activated with relative humidity set to 55% RH and the fan running continuously. In summer conditions (above 27˚C outside), the system will run as an air-conditioner and rejecting heat to the outside through the outside supplemental condenser; however the fan running continuously.

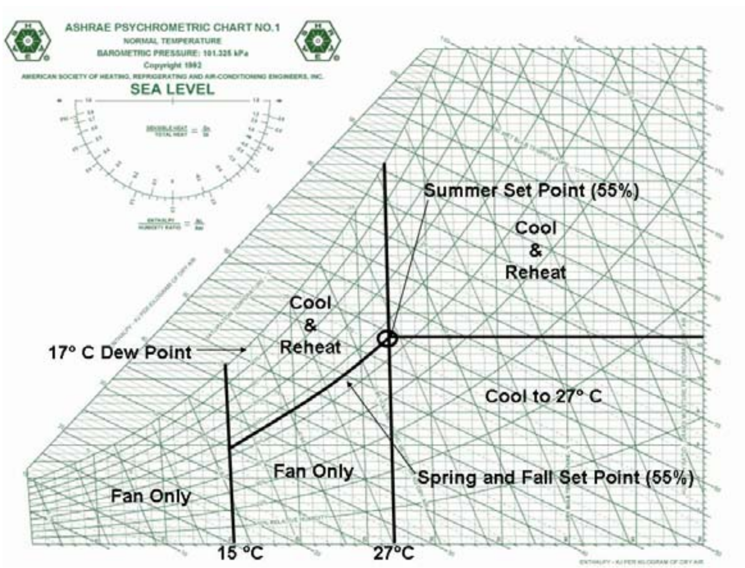

Figure 2 Psychrometric chart describing operation and control regimes of the climate control system

RESULTS

<u>Building envelope improvements</u>
As the first important step in the building's climate improvement effort, the project focused on both the thermal characteristics and air-tightness of the building envelope. For improved thermal characteristics, it was essential to provide thermal insulation to only visually and aesthetically acceptable areas. New double-glazed windows with internal shades and ultraviolet filters were incorporated into the original decorative grills of the windows. Gaps created by warped entry doors and door frames were sealed using sponges enclosed in a textile with historic patterns. Rafters and base beams of the roof had large gaps due to shrinkage of the rafters. These gaps were sealed using an injection type of polyurethane form. The tighter envelope limits the infiltration of polluted Beijing air.

<u>Mechanical system</u>
The mechanical system was initially installed in November 2007. After two separate inspections and subsequent minor corrections, the system was accepted and its performance was carefully monitored for one year (the HVAC contractor's warranty period). The climate control system installed in Juanqinzhai has 20 kW cooling and 18 kW re-heat (through the hot gas re-heat) capacities. It has a highly efficient, yet low-cost to maintain, three phase filter system (washable and disposable pleated filters, washable bag filters, and HEPA filters) and a capacity to re-circulate the air within the building six times per hour to continuously

trap/capture particulate matter entered into the building through minute holes and cracks of the building or when entrance doors are opened for tours.

The air handler is located in a newly created machine room that divides the attic of Juanqinzhai in two equal halves. The room is lined with a sound absorbing material for containing noise generated by the air handler to ensure a quiet interior. The air handler is mounted on a vibration-isolated frame suspended from beams that support the roof structure to eliminate sound transmission through internal walls and ceiling. The supply and return air openings, which contain four airfoil shaped wings made of perforated aluminum sheet for noise suppression, are connected to ends of the air handler through a connector with a 90˚ bend that is connected to the air handler through a flexible boot. The air velocity is limited to 2.5 m/s in the air handler, air ducts, and diffuser grills to limit the aerodynamic noise.

The supply air opening of the air handler is located on the machine room's western wall at the north end to the western half of the attic; this became a large supply air manifold (Figures 3 and 4). A large supply air grill to the western (theater) half of the occupied/visited area of the building is positioned at the second floor ceiling above the emperor's theater viewing seat. The conditioned air flows from the theater half to the eastern (reception and resting area) half of the building through corridors on the 1st and 2nd floors. The return air grill is located on the ceiling of a 2nd floor room at the northeast end of the building. Similar to the western half of the attic, the eastern attic is converted to a return air manifold. The attic air returns to the air handler through a duct opening located at the southwest end of attic wall that is the eastern wall of the machine room.

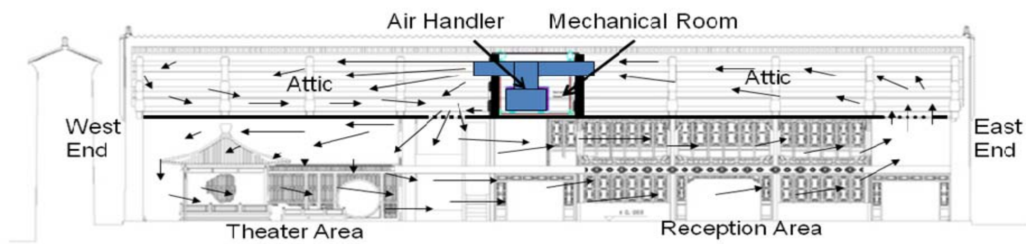

Figure 3 Locations of mechanical room and air handler and flow pattern of conditioned air.

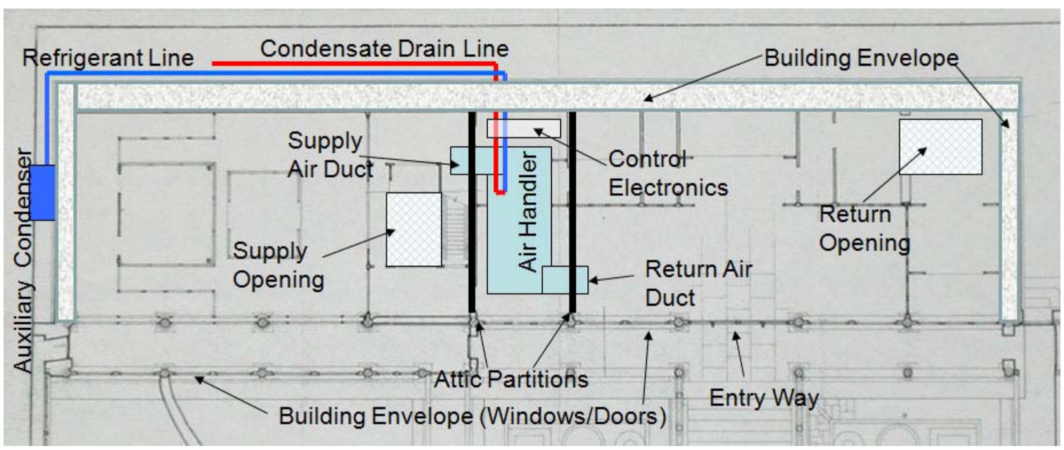

Figure 4 Floor plan and locations of climate control system's components

A large flat stainless steel pan is placed under the entire air handler, the condensate drain and refrigerant lines. It has water sensors which sound an audible alarm and shut off the power to the mechanical system when any one of them senses water. By gravity, a condensate drain line drains to an underground drain system located behind (north of) the building. The DX compressor and supplemental condenser are placed outside at the west end of the building hidden away from visitor view. (Figure 4)

Control system

The control of climate system components consists of a CPU, several I/O modules, sensors and switches, a data collection/storage module, and a keypad and display unit. (Figure 5) The controlling sensors are located at the return air and supply air ducts. And the keypad and display unit is mounted on a second floor wall just below the mechanical room in the attic. The CPU, I/O modules, and storage module are placed in a metal cabinet in the mechanical room. Sensor readings are processed by the CPU and commands are sent to the I/O modules for switching various components. The operational data of the system and sensor readings are stored in the data collection/storage module. The keypad and display unit allows not only viewing of all operational parameters and sensor readings, but also it allows the operator to modify the parameters. The control system in the building is connected to an Ethernet interface device through which a dedicated PC (with proprietary software) in the Palace Museum's network accesses the system. Outside PCs, such as one at a maintenance contractor's office, can access the system by logging into the dedicated PC in the Palace Museum via Windows' Remote Desktop Connection software.

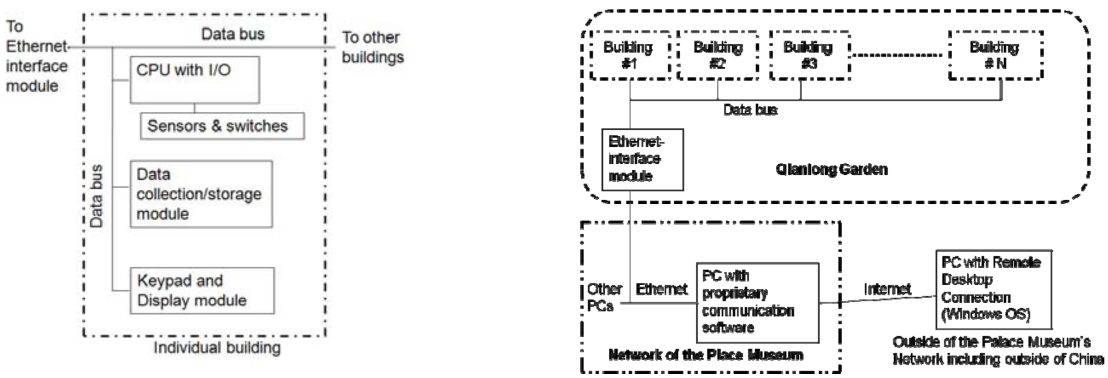

Figure 5 Schematics of a climate control station in individual buildings (left) and a proposed network of climate control stations in Qianlong Garden (right)

Performance

After acceptance of the mechanical system, the temperature and relative humidity were measured at eight locations throughout the building, three locations in the air handler, and the outside for performance evaluation. Juanqinzhai maintained levels of relative humidity above 40% and below 55% in the building during the first year of its operation, although the outside temperature varied from 0˚ to 28˚C. The climate control strategy has successfully reduced the annual variation of relative humidity from 90% in a year to only 15% and completely eliminated the spatial variation of the climate. Measurements of airborne particulates have proven that the combination of air-tightening of the building envelope and the operation of the high performance filter system has successfully controlled the dust problem. Noise levels are less than 50 dB and 47 dB near the machine room and the rest the building, respectively.

DISCUSSION

A minimally intrusive and conservation-focused climate control strategy was successfully developed and implemented for Juanqinzhai. The strategy was primarily to maintain the conservation environment for its historic interior. The mechanical system was successfully designed, installed and operated in the building. Noise levels have been acceptable, and the dust problem has been successfully controlled.

Although we have been successful in maintaining the preservation environment for the building and its interior, we have not been able to provide comfort for visitors at both extreme high and low temperature conditions. It is possible, however, to modulate the air change rate (air movement) during hot and cold days for comfort.

The Palace Museum implemented the use of shoe covers for visitors to Juanqinzhai. However, the covering of shoes is done at the reception area in the building, allowing visitors to transport dust into the building. We strongly recommend the creation of an entry vestibule area to reduce infiltration of the uncontrolled outside air during the visitor entry/exit to the building as well as the placement/removal of shoe covers.

There has been a longstanding policy of fire prevention within the Forbidden City by turning the electricity off at night (between 5 pm and 9 am daily). Repeated requests have been made to the authority since the installation of a mechanical climate system was approved, that 24/7 continuous delivery of electricity is necessary for the mechanical system to operate properly. A similar request was also made for the installation of a network line in the building. Unfortunately, both requests are still pending. We may find unexpected problems to develop in the future due to the intermittent power and/or online access of the system.

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