Basic buildings physics for low energy climate control in museum buildings

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The main purpose of the museum building is to protect the artifacts against the natural environment. The building envelope is continuously exposed to the variable climatic conditions, and should moderate changes over the day or the year. The climatic parameters are heat and radiation, humidity and precipitation (rain, snow), wind and convection. These are the main sources for energy loss and gain in buildings. There are other important environmental parameters for museums buildings, such as light and sound (noise) or pollutants and pests. The building structure may occasionally be subjected to mechanical impact, and should be designed to survive such events. The common accident and disasters are fire, earthquakes, floods, storms. This paper will only deal with the climatic influence.

Heat and radiation

The temperature of the outside air is mainly controlled by meteorological processes and will change over the day and year. Heat gain from the sun and heat loss by radiation to the sky will lead to temperature differences on exposed surfaces within minutes and hours. The building envelope should be designed to moderate the heat flow in and out of the building both on short and long term. The choice of material and the thickness of the building component depend on the duration and the magnitude of the temperature variation. The mathematical analysis of this phenomenon is based on an analogy to the damped harmonic swing. When a sine wave progresses into a substance, the outer limits form a trumpet-shaped curve, which indicates how thick the wall should be to obtain a certain reduction of amplitude. A reduction to 37% of the original amplitude is used as a reference for the periodical penetration depth

The ability to reduce temperature variations is a combination of the thermal conductance and thermal capacity of the material. Concrete has a high thermal capacity, but a low thermal resistance. A concrete wall must be 15 cm thick to reduce the amplitude of a 24 hours harmonic temperature swing to 37 % of the original. The thermal inertia of concrete may be improved by embedding very small bubbles of wax in the structure. The wax is designed to melt at a specific temperature. The energy needed for this phase transition adds to the total heat capacity of the structure. What if the wall is instead made of mineral wool, which gives a much better thermal insulation? Mineral wool has a low heat capacity but a high thermal resistance. The thickness of a mineral wool wall must also be 15 cm to get the same 63% reduction of amplitude. These two materials have very different thermal properties, but they perform equally in terms of thermal inertia. A wooden wall needs only to be 7 cm thick, because this material has moderate heat capacity and thermal conductance. A steel wall must be 65 cm thick due to good thermal conductivity. A combination of materials works better, because the reduction in amplitude is largest in the first 10-15 cm. A cavity wall of 10 cm cellular concrete and 11 cm brick with 15 cm mineral wool in between will reduce daily variations in temperature by 95%.

The roof of a building will experience the same daily fluctuations as the walls. But on top of this comes the heat gain with radiation from the sun during daytime and heat loss to the open sky at night. The heat transfer due to radiation can either be reduced or enhanced with the choice of roof material. A metal roof with a blank surface will reflect most of radiation, but will also heat op quickly because of the small heat capacity. The hot metal will radiate heat further down into the attic, which then becomes warm. At night the metal roof emits little heat to the sky and keeps the building above the daily average. This may increase the need for ventilation or even cooling during daytime. Glazed tiles provide some protection against radiant heat. The glazed surface reflects more radiation than normal tiles, and absorbs more heat than thin metal sheets. Glass roofs allow much more heat into the building during daytime and seriously affect the thermal conditions for the building. This is a benefit in cold climates but inconvenient in warmer locations. Some types of glass will reflect a part of the radiation, but may alter the colour rendering of the transmitted light. Curtains or variable screens will adjust the solar impact, but they must be outside to reduce the heating. The roof is a good place to mount solar panels and solar collectors, which can be used to adjust the temperature of the building by mechanical means (see below).

Walls and roofs with a normal thickness are able to moderate diurnal temperature variations. Only very heavy structures can level out the annual variation, which are typical for temperate climate zones. Underground spaces have a constant temperature which is the annual average of the ambient temperature above ground. The floor of a building can act as a heat sink, which will moderate the temperature over the year. In summer the heat is taken up and in winter it is released to the interior again. To obtain the appropriate thickness for thermal inertia, the floor should not be insulated. This only works for buildings in one level with a large floor area. The annual average temperature will be close to the outside average, or a little above because of the heat gain by radiation. If this is not sufficient for human comfort or humidity control (see below), there must be an additional source of heat. Heat can be moved from the roof and stored under the building by active systems such as water circulating in pipes or air blown through ducts. A heat pump can extract heat from the ground or the air by. Some heat pumps can work reverse and cool the building if needed.

Humidity and precipitation

The rain or snow is a source of moisture to the building and should be screened away by a sloping roof and drained facade. The rain water may be collected and reused for humidification of the interior or to cool down the building by evaporation. Green roofs will absorb the rain and let it evaporate, but this is only a benefit if there is a surplus of heat. Leaky roofs are a risk to both the building and the objects within it. In regions with much rain one should prefer a double roof construction or a ventilated attic. This will also be a benefit for temperature control.

The humidity of the space is usually quoted in grams of water vapour per cubic meter. The relative humidity is the actual vapour content divided by the maximum vapour content of the space at the specific temperature. The vapour is an invisible gas, that mixes with the other gases of the atmosphere and exercises a 'vapour presure', which is very little compared to the total air pressure. The water vapour content of the outside air changes over the day and is also drifting over the year. The vapour evaporates from the ground or water surfaces, or from plants and animals. Human activity generates humidity inside the houses by cooking and cleaning. The water vapour enters or leaves the buildings mainly with the air infiltration (see below), but not (as often claimed) due to a 'vapour pressure difference'.

If the vapour content reaches the point of saturation, the vapour condenses and there will be fog or mist, which is small water drops (aerosols) held up by air movements. Sometimes the condensation takes place on a cold surface, which has reached the dew point. The heat of condensation is quite large (2500 kJ/kg), but the heat released by the water vapour is rather little because there is not much of it. In one cubic meter of air at 20 C and 50% RH there is approximately 7,2 grams of vapour. The energy needed to heat up the dry air from 0 C is 24 kJ and the energy used to evaporate and heat the water vapour from 0 C (latent heat) is 21,5 kJ. The energy figures (or rather enthalpy) can be read out of the mollier diagram, which is an advanced type of water vapour diagram.

The indoor water vapour concentration can be controlled by a mechanical (de)humidifier. There are two types of dehumidifiers: A condensing dehumidifier will cool the air to the dew point, and collect the condensed moisture in a bucket or let it run to a drain. An absorption dehumidifier will remove the surplus of moisture by absorbing it into a perforated disc lined with silica gel. The humidity is released by blowing heated outside air through the revolving disc. Both devices use energy to do this, although in theory the dehumidification would release energy. But dehumidification is a quite efficient way of controlling the RH. Humidification is usually done by injecting steam into the ventilation ducts, or by spraying water mist into the room and let it evaporate. The last option is common in the fruit and vegetable corner of a supermarket, where it also cools down the air and removes excess heat from lamps and people.

Some building materials have the ability to moderate the water vapour concentration of the air, without any supply of energy. The humidity buffer capacity is described in the paper ‘limits for moisture buffer’ and in the lecture ‘The use of building materials to moderate the RH’

Wind and convection

The wind creates a pressure difference around the building, which generates air movements through leakages and holes in the building envelope. If the wind is frequent and strong, and the building is very leaky, the inside climate will be almost similar to the outside. For any building with a controlled indoor climate, it is important to make the building as air tight as possible. Historic buildings are usually rather leaky, but modern buildings can be made very air tight thanks to elastic sealants and plastic foils. Keeping the air exchange rate as little as possible is fundamental for low energy climate control in stores and archives. The air exchange rate is quoted in air changes per hour (h^{-1}), which is the volume of outside air that infiltrates the volume of the building (or room) in one hour.

In museum buildings with human occupation, there is some need for air exchange. For this reason most exhibition spaces have mechanical ventilation, which is designed to give a ventilation rate of four times per hour or even more. The wind can replace such power consuming systems, if the building is designed to use natural ventilation. Ducts and chimneys must be located to make best possible use of the wind at all directions. Because the wind is not constant, there must be enough space to provide a reservoir of fresh air. Tall exhibition spaces are in favor for natural ventilation. Natural ventilation also works due to different temperatures. Warm air has less density than cold air and will therefore be lighter and move upwards. In tall rooms this ‘stack effect’ will enhance the natural ventilation in winter. This is the driving force in solar chimneys, where the solar heating of a vertical space extracts air from the spaces below.

The wind is also a powerful source of sustainable energy. The infrequent nature of this energy source is not a problem for buildings with thermal stability and humidity buffer capacity. The building act as a reservoir, which is filled from time to time, but will survive days of little wind.