

Baker House Dining Room: Thermal Balance Report

For this project, we chose to analyze the thermal balance of Alvar Aalto's Baker House Dining Room. In order to determine the thermal equilibrium and thus the heating requirements of the dining hall, we need to examine the heat gains and losses due to a variety of factors throughout the course of a day. Specifically, we will look at four times during an average March day: 3 H, or about 3 am, 9H, or about 9 am, 15H, or about 3 pm, and 21H, or about 9pm, and attempt to find the heating requirements needed to maintain thermal balance by calculating the heat transfer due to other internal gains, conduction, solar gains, ventilation, and evaporation.

$$Q_i + Q_c + Q_s + Q_v + Q_e = 0$$

1 Calculating Q_i

$$Q_i = Q_{people} + Q_{appliances} + Q_{heating} + Q_{lighting}$$

The dining room is connected to a serving area and a communal kitchen area for students. However, we can assume that there is negligible heat exchange between the dining room and kitchen and serving areas in order to simplify the problem. We assume that both of these rooms mechanically ventilate the heat generated by appliances and cooking out of the spaces via ductwork independent of the main dining room. Additionally, because the kitchen space is underused, it is likely that even without the separate ventilation system the thermal impact and involvement of the space would be minimal.

Therefore, the only appliance in the vicinity of Baker Dining that we consider is an ice maker. The wattage of the ice maker is estimated through comparison with a similar machine researched on the web. The heat emission for the room's electric lights can also be calculated based on the number of lights and an estimated wattage of 5W per light:

$$Q_{appliances, 3H} = Q_{appliances, 9H} = Q_{appliances, 15H} = Q_{appliances, 21H}$$

$$Q_{appliances, xH} = Q_{ice\ maker} = 350\ W$$

$$Q_{lighting, 3H} = Q_{lighting, 9H} = Q_{lighting, 15H} = Q_{lighting, 21H}$$

$$Q_{lighting, xH} = (30\ lights)(5W / light) = 150W$$

Baker Dining is primarily used in the evening by residents. At any given time in the evening, we estimate that the number of people inhabiting the space was fifty people. During the day, the dining area is not usually trafficked by more than a few people at a time.

$$Q_{people, 3H} = Q_{people, 9H} = 0W$$

$$Q_{people, 15H} = (2\ people)(150W / person) = 300W$$

$$Q_{people, 21H} = (50\ people)(150W / person) = 7500W$$

We can sum these value to find the total internal heat gains (besides the mechanical heating) for each of our four times:

$$\begin{aligned}
Q_{i,3H} &= Q_{app,3H} + Q_{lrg,3H} + Q_{ppl,3H} + Q_{ht,3H} = 350W + 150W + 0W + Q_{ht,3H} = +500W + Q_{ht,3H} \\
Q_{i,9H} &= Q_{app,9H} + Q_{lrg,9H} + Q_{ppl,9H} + Q_{ht,9H} = 350W + 150W + 0W + Q_{ht,9H} = +500W + Q_{ht,9H} \\
Q_{i,15H} &= Q_{app,15H} + Q_{lrg,15H} + Q_{ppl,15H} + Q_{ht,15H} = 350W + 150W + 300W + Q_{ht,15H} = +800W + Q_{ht,15H} \\
Q_{i,21H} &= Q_{app,21H} + Q_{lrg,21H} + Q_{ppl,21H} + Q_{ht,21H} = 350W + 150W + 7500W + Q_{ht,21H} = +8000W + Q_{ht,21H}
\end{aligned}$$

2 Calculating Q_c

Baker Dining has essentially three exterior boundary conditions: single pane glass, double pane low-e glass, and 16" composite walls. To calculate the heat lost through the walls via conduction, we first need to find the individual heat loss through each of these surface types:

$$\begin{aligned}
Q_c &= Q_{c,wall} + Q_{c,single\ glass} + Q_{c,double\ glass} \\
Q_c &= (A_{wall} \cdot U_{wall} + A_{single\ glass} \cdot U_{single\ glass} + A_{double\ glass} \cdot U_{double\ glass}) \cdot \Delta T
\end{aligned}$$

Based on observations and conversations with Jon Nolan, the Baker House manager, we've determined that the wall composition is brick on the interior, solid CMU at the core, a small air gap for reducing inward moisture flow, a nailing substrate, and limestone facing on the exterior, interestingly with no insulation. From this, we can calculate the U-value for the wall:

$$\begin{aligned}
U_{wall} &= \left(\sum \frac{b_i}{\lambda_i} \right)^{-1} = \left(0.06m^2 \cdot K/W + \frac{3.5in \cdot 0.0254m/in}{0.84W/m \cdot K} + \frac{8in \cdot 0.0254m/in}{1.63W/m \cdot K} + 0.12m^2 \cdot K/W \right. \\
&\quad \left. + 0.12m^2 \cdot K/W + \frac{1.5in \cdot 0.0254m/in}{0.138W/m \cdot K} + \frac{2in \cdot 0.0254m/in}{1.30W/m \cdot K} + 0.12m^2 \cdot K/W \right)^{-1} \\
U_{wall} &= 0.79^{-1} W/(m^2 \cdot K) = 1.39 W/(m^2 \cdot K)
\end{aligned}$$

We can use the 2001 *ASHRAE Fundamentals Handbook* to find the U-values for the two window types:

$$U_{single\ glass} = 5.91 W/(m^2 \cdot K) \quad U_{double\ glass} = 2.69 W/(m^2 \cdot K)$$

The areas for each surface type were found through a combination of on-site measurement and examination of construction documents. Because it will be helpful later for calculating solar heat gains, we will consider each of the 4 exterior walls independently before summing their areas.

$$\begin{array}{cccccc}
A_{wall,1} = 32.53m^2 & A_{wall,2} = 25.26m^2 & A_{wall,3} = 40.45m^2 & A_{wall,4} = 6.33m^2 & A_{wall,tot} = 104.57m^2 \\
A_{1gls,1} = 4.67m^2 & A_{1gls,2} = 17.11m^2 & A_{1gls,3} = 16.22m^2 & A_{1gls,4} = 1.55m^2 & A_{1gls,tot} = 39.55m^2 \\
A_{2gls,1} = 0m^2 & A_{2gls,2} = 9.13m^2 & A_{2gls,3} = 12.96m^2 & A_{2gls,4} = 0m^2 & A_{2gls,tot} = 22.09m^2
\end{array}$$

Based on empirical qualitative findings as well as research into general standards, we chose the following temperatures for the interior and exterior at our four times:

$$\begin{array}{cccc}
T_{e,3H} = -0.5^\circ C & T_{e,9H} = 2.0^\circ C & T_{e,15H} = 5.0^\circ C & T_{e,21H} = 1.5^\circ C \\
T_{i,3H} = 19.0^\circ C & T_{i,9H} = 20.0^\circ C & T_{i,15H} = 24.0^\circ C & T_{i,21H} = 21.5^\circ C \\
\Delta T_{3H} = -19.5K & \Delta T_{9H} = -18.0K & \Delta T_{15H} = -19.0K & \Delta T_{21H} = -20.0K
\end{array}$$

We must also consider that a portion of the lower part of the dining hall is below grade, so the walls here conduct heat not to the outside air, but to the earth. For this part of our calculations we need a slightly different U-value for the wall which omits the exterior surface film resistance, as there is no air layer

between the wall and the earth, as well as the air gap and limestone cladding which probably do not continue below ground level:

$$U_{\text{wall-below grade}} = \left(\frac{3.5 \text{ in} \cdot 0.0254 \text{ m/in}}{0.84 \text{ W/m} \cdot \text{K}} + \frac{8 \text{ in} \cdot 0.0254 \text{ m/in}}{1.63 \text{ W/m} \cdot \text{K}} \right)^{-1} = 3.44 \text{ W}/(\text{m}^2 \cdot \text{K})$$

We weren't able to find or collect values for the ground temperature, but given the lag due to the large thermal mass of the earth, we estimate the ground is colder than the air in March, probably measuring about -2°C. Therefore, the temperature difference values for the below grade parts of the walls are:

$$\Delta T_{3H} = -21.0\text{K} \quad \Delta T_{9H} = -22.0\text{K} \quad \Delta T_{15H} = -26.0\text{K} \quad \Delta T_{21H} = -23.5\text{K}$$

We also measured the wall areas of the portions of the wall that were below grade:

$$A_{\text{wall-bg},1} = 0\text{m}^2 \quad A_{\text{wall-bg},2} = 28.99\text{m}^2 \quad A_{\text{wall-bg},3} = 16.16\text{m}^2 \quad A_{\text{wall-bg},4} = 8.08\text{m}^2 \quad A_{\text{wall-bg,tot}} = 53.25\text{m}^2$$

With these values, we can now solve for Q_c loss through the walls throughout the day using the equation above.

$$\begin{aligned} Q_{c,3H} &= (104.57\text{m}^2 \cdot 1.39 \text{ W}/(\text{m}^2 \cdot \text{K}) + 39.55\text{m}^2 \cdot 5.91 \text{ W}/(\text{m}^2 \cdot \text{K}) + 22.09\text{m}^2 \cdot 2.69 \text{ W}/(\text{m}^2 \cdot \text{K})) \cdot -19.5\text{K} \\ &\quad + 53.25\text{m}^2 \cdot 3.44 \text{ W}/(\text{m}^2 \cdot \text{K}) \cdot -21.0\text{K} = -12409.41\text{W} \\ Q_{c,9H} &= (\dots) \cdot -18.0\text{K} + (\dots) \cdot -22.0\text{K} = -11934.3\text{W} \\ Q_{c,15H} &= (\dots) \cdot -17.0\text{K} + (\dots) \cdot -26.0\text{K} = -13106.54\text{W} \\ Q_{c,21H} &= (\dots) \cdot -19.0\text{K} + (\dots) \cdot -23.5\text{K} = -13087.19\text{W} \end{aligned}$$

A lot of heat is also conducted through the roof and the twenty-four skylights that populate it, so we must count this heat loss in our total Q_c as well. We can approximate the roof's composition by finding the best match in *Introduction to Architectural Science's* Data Sheet D.1.4, which is the concrete slab flat roof and has a U-value of 1.80W/m²K. The roof's area is 166.51m².

The skylights are made of frosted single-pane glass and have a U-value of 9.82W/m²K, according to *ASHRAE*. Their total area is 15.75m². We can calculate our final conductance heat losses by combining the effects of the roof and skylights with what we've already computed:

$$\begin{aligned} Q_{c,3H} &= -12409.41\text{W} + (166.51\text{m}^2 \cdot 1.80 \text{ W}/\text{m}^2 \cdot \text{K} + 15.75\text{m}^2 \cdot 9.82 \text{ W}/\text{m}^2 \cdot \text{K}) \cdot -19.5\text{K} = -21269.88\text{W} \\ Q_{c,9H} &= -11934.3\text{W} + (\dots) \cdot -18.0\text{K} = -20113.19\text{W} \\ Q_{c,15H} &= -13106.54\text{W} + (\dots) \cdot -19.0\text{K} = -21739.82\text{W} \\ Q_{c,21H} &= -13087.19\text{W} + (\dots) \cdot -20.0\text{K} = -22174.85\text{W} \end{aligned}$$

3 Calculating Q_s

During two of our testing times, Baker Dining Room experiences large heat gains due to solar radiation through both the transparent and opaque surfaces of the building. We can calculate these gains through the following equation:

$$Q_s = A_{\text{transparent}} \cdot SHGF \cdot SC + A_{\text{opaque}} \cdot U_{\text{opaque}} \cdot dTe$$

The SHGF (solar heat gain factor) is a value given in *ASHRAE* for a given latitude, month, time, and orientation, and the SC (shading coefficient) corrects the SHGF if less transmissive glazing is used. For Baker House Dining Room, the closest orientation for the four walls are Wall 1 = NW, Wall 2 = SW, Wall 3 = SE, and Wall 4 = NE and their SHGF are as follows:

<i>h</i>	Wall 1 (NW)	Wall 2 (SW)	Wall 3 (SE)	Wall 4 (NE)
3H	0	0	0	0
9H	67 W/m ²	69 W/m ²	743 W/m ²	147 W/m ²
15H	147 W/m ²	743 W/m ²	69 W/m ²	67 W/m ²
21H	0	0	0	0

The shading coefficient for the single pane glazing is 1.0, since the glazing makes no improvements. The double pane low-e glazing has an SC of 0.76. We can now calculate the heat gain through the two window types due to solar radiation using the area values given in the calculations of conductive heat loss

$$Q_{s,transparent,9H} = (4.67\text{m}^2 \cdot 1.0 + 0\text{m}^2 \cdot 0.76) \cdot 67\text{W/m}^2 + (17.11\text{m}^2 \cdot 1.0 + 9.13\text{m}^2 \cdot 0.76) \cdot 69\text{W/m}^2 + (16.22\text{m}^2 \cdot 1.0 + 12.96\text{m}^2 \cdot 0.76) \cdot 743\text{W/m}^2 + (1.55\text{m}^2 \cdot 1.0 + 0\text{m}^2 \cdot 0.76) \cdot 147\text{W/m}^2 = +21569.07\text{W}$$

$$Q_{s,transparent,15H} = (4.67\text{m}^2 \cdot 1.0 + 0\text{m}^2 \cdot 0.76) \cdot 147\text{W/m}^2 + (17.11\text{m}^2 \cdot 1.0 + 9.13\text{m}^2 \cdot 0.76) \cdot 743\text{W/m}^2 + (16.22\text{m}^2 \cdot 1.0 + 12.96\text{m}^2 \cdot 0.76) \cdot 69\text{W/m}^2 + (1.55\text{m}^2 \cdot 1.0 + 0\text{m}^2 \cdot 0.76) \cdot 67\text{W/m}^2 = +20455.97\text{W}$$

There is also solar heat gain caused by radiation that enters through the skylights, which according to *ASHRAE* have a SC of 0.28 due to their translucence. The SHGF for horizontal surfaces is 450 W/m² for both 9H and 15H. We can add the effect of the skylights to the results above to find the total solar heat gain through the building's transparent surfaces.

$$Q_{s,transparent,9H} = 21569.07\text{W} + 15.75\text{m}^2 \cdot 450\text{W/m}^2 \cdot 0.28 = +24665.42\text{W}$$

$$Q_{s,transparent,15H} = 20455.97\text{W} + 15.75\text{m}^2 \cdot 450\text{W/m}^2 \cdot 0.28 = +22440.81\text{W}$$

Now, we need to calculate the heat gain from solar irradiation on the building's exterior walls and roof. As in part of the conduction losses calculations, we will only count the above-ground level wall area. We can use the equation given at the beginning of this section, but we need to define dTe: $G \cdot \alpha \cdot R_{so}$, where *G* is the global irradiance incident on the walls, α is the absorptance value of the surface, and R_{so} is the resistance of the outer air layer, 0.06 m²K/W. *G* depends on the angle of incidence of the solar radiation, which in turn depends on the latitude, day, time, and orientation of the surface in question, and has been calculated for each wall.

<i>h</i>	Wall 1 (NW)	Wall 2 (SW)	Wall 3 (SE)	Wall 4 (NE)
3H	0	0	0	0
9H	0	0	1575.98 W/m ²	239.99 W/m ²
15H	0	1048.01 W/m ²	46.15 W/m ²	0
21H	0	0	0	0

If we take α to be 0.4, the value that Data Sheet D.1.2 gives for light brick (as an approximation of the limestone), we can find the dTe values for each wall at each time and thereby find the solar heat gain through the walls:

$$Q_{s,opaque,9H} = 40.45\text{m}^2 \cdot 1.39\text{W/m}^2\text{K} \cdot (1575.98\text{W/m}^2 \cdot 0.4 \cdot 0.06\text{m}^2\text{K/W}) + 6.33\text{m}^2 \cdot 1.39\text{W/m}^2\text{K} \cdot (239.99\text{W/m}^2 \cdot 0.4 \cdot 0.06\text{m}^2\text{K/W}) = +1426.4\text{W}$$

$$Q_{s,opaque,15H} = 25.26\text{m}^2 \cdot 1.39\text{W/m}^2\text{K} \cdot (1048.01\text{W/m}^2 \cdot 0.4 \cdot 0.06\text{m}^2\text{K/W}) + 40.45\text{m}^2 \cdot 1.39\text{W/m}^2\text{K} \cdot (46.15\text{W/m}^2 \cdot 0.4 \cdot 0.06\text{m}^2\text{K/W}) = +920.57\text{W}$$

Again, we must also consider the effect of the roof. Dte for the roof is given as $(G \cdot \alpha - E) \cdot R_{so}$, where E is the radiant emission of the roof and can be taken to be 90W/m^2 for a clear day. G is calculated to be 888W/m^2 , and we can take α to be 0.9, the value given in D.1.2 for asphalt roofing surface. R_{so} is $0.04\text{m}^2\text{K/W}$ for roofs, according to D.1.2 as well. With this information, we can find the total solar gain from radiation on opaque surfaces:

$$Q_{s, \text{opaque}, 9\text{H}} = 1426.4\text{W} + 166.51\text{m}^2 \cdot 1.8\text{W/m}^2\text{K} \cdot (888\text{W/m}^2 \cdot 0.9 - 90\text{W/m}^2) \cdot 0.04\text{m}^2\text{K/W} = +9928.97\text{W}$$

$$Q_{s, \text{opaque}, 15\text{H}} = 920.57\text{W} + 166.51\text{m}^2 \cdot 1.8\text{W/m}^2\text{K} \cdot (888\text{W/m}^2 \cdot 0.9 - 90\text{W/m}^2) \cdot 0.04\text{m}^2\text{K/W} = +9423.2\text{W}$$

Now we can combine the heat gains through transparent and opaque surfaces to find the total gains.

$$Q_{s, 9\text{H}} = 24665.42\text{W} + 9928.97\text{W} = +34594.38\text{W}$$

$$Q_{s, 15\text{H}} = 22440.81\text{W} + 10227.57\text{W} = +31864.01\text{W}$$

4 Calculating Q_v

$$Q_v = (1200\text{J/m}^3\text{K}) \cdot nV$$

Online data indicated that the air change rate for dining halls was between twelve and fifteen air changes per hour (http://www.engineeringtoolbox.com/air-change-rate-room-d_867.html). We will assign the value of n as:

$$n = 13.5 \text{ air changes / hr} = .0038 \text{ air changes / sec}$$

The volume of Baker Dining is calculated by taking the composite volume of the upstairs and downstairs dining areas as well as the total volume of the skylights.

$$V_{\text{Total}} = V_{\text{upstairs}} + V_{\text{downstairs}} + V_{\text{skylights}}$$

$$V_{\text{upstairs}} = (1683\text{ft}^2) \left(\frac{124\text{in} \cdot \text{ft}}{12\text{in}} \right) = 17,391\text{ft}^3$$

$$V_{\text{downstairs}} = (3395\text{ft}^2) \left(\frac{116\text{in} \cdot \text{ft}}{12\text{in}} \right) = 32,818\text{ft}^3$$

$$V_{\text{skylights}} = (24 \text{ skylights}) \left(\frac{74\text{in} \cdot \text{ft}}{12\text{in}} \right) (1.5\text{ft})^2 \cdot \pi = 1,046\text{ft}^3$$

$$V_{\text{Total}} = 51,255\text{ft}^3 = 1,451\text{m}^3$$

$$Q_v = (1200\text{J/m}^3\text{K})(-.0038 \text{ air changes / sec})(1,451\text{m}^3) = -6,617\text{W}$$

5 Calculating Q_e

We assume that the evaporative losses and gains are negligible, thus $Q_e = 0$.

6 Thermal Equilibrium

$$(Q_i - Q_{heating}) + Q_{heating} + Q_c + Q_s + Q_v + Q_e = 0$$

$$Q_{heating} = -[(Q_i - Q_{heating}) + Q_c + Q_s + Q_v + Q_e]$$

Heating requirements (four cases):

$$Q_{heating, 3H} = -(500W - 21269.88W + 0W - 6617W) = +27,386.88 W$$

$$Q_{heating, 9H} = -(500W - 20113.19W + 34594.38W - 6617W) = -8,364.19 W$$

$$Q_{heating, 15H} = -(800W - 21739.82W + 31864.01W - 6617W) = -4,307.19 W$$

$$Q_{heating, 21H} = -(8000W - 22174.85W + 0W - 6617W) = +20,791.85 W$$

These are the values needed to maintain a steady-state thermal equilibrium throughout the day. However, we could use significantly less mechanical heating at night if we store the excess heat that appears at 9H and 15H during the day in thermal mass and then use it at night to heat the building. Assuming that we can store 60% of the excess heat that the building receives during the day to help passively heat it during the night, we would still need between about 14 to 21 kW heat at night. As a point of comparison, a microwave oven produces about 1.3kW of heat, so we would need the equivalent of around 11 to 16 operating microwaves to maintain the daily thermal balance.