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A Comparative Study on Thermal Load Calculation Methods for a Residential Building

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Abstract

Some essential objectives in energy sector may be considered to provide low-carbon cities, increase share of renewables and maintain relatively higher efficiencies in both fuel consumption and energy utilization fields. A thermal load calculation plays a key role for achieving these objectives by determining amount of energy consumption in related sectors. Due to high energy consumption (32%) and high carbon dioxide emission (30%) percentages in global scale, thermal load calculations were carried out for an educational building while these calculations were used to size a HVAC system, which amounts to nearly half of total building’s energy consumption. In this study, four different methods are carried out for determining the capacity of a split type air conditioner unit in a single room of Ege University’s mechanical engineering department building. The methods considered include (i) a Turkish Standard (TS) 825 simulation program, that is quite popular in Turkey, (ii) a marketplace calculation tool, (iii) an Open Studio program based on Energy Plus and (iv) ASHRAE Handbook 2013 residential cooling and heating load calculations procedure.

In this study, the building envelope, internal heat gains, ventilation, infiltration and atmospheric conditions were regarded as input parameters first. Then, both maximum heat gain and heat loss amounts in terms of peak loads were calculated using four different methods for sizing the HVAC system. Finally, the calculation steps of the methods used along with their basic advantages and disadvantages were discussed. It may be concluded that ASHRAE Handbook 2013 residential cooling and heating load calculations procedure was chosen as a main method because it offered more accurate calculation.

Keywords - thermal load calculation, HVAC sizing, simulation program
1. Introduction

HVAC systems became a standard equipment for both residential and non-residential buildings to provide comfort parameters. As it is well known, parallel to technological development in business life, kind and number of electronic appliances are increased which led to additional heat gain. These heat gains have to be removed for keeping employees’ work performance in a specific level. This can be performed by conditioning an office to specific temperature and humidity values with suitable air velocity levels. For example, after 25 °C temperature value, each of 1°C increase causes 2% consideration loss in working [1].

Two types of procedures, namely on site measurement and forecasting, can be used in thermal load calculations. Since onsite measurement procedure is not economically feasible and requires long time, studies done up to concentrate on forecasting by statistical methods or simulation programs. Statistical method requires hourly energy consumption data and their analysis and it based on linear regression, exponential correction, grey box theory, neural network, etc. and their different combinations. On the other hand, energy simulations methods like as Open Studio, TS-825, DOE-2, Energy-Plus, TRNSYS, HTB2, HKDLC, BECON, etc. requires lots of detailed data about building (building geometry, material, radiation and so on). Also it has to be noted that each of these programs has own difficulties [2].

In this study instantaneous peak load calculation for determining HVAC system capacity was carried out for a single room which is given with Fig. 1. While making these calculations two of energy simulation programs, namely Open Studio and TS-825 are used. Besides, a marketplace calculation tool and ASHRAE Handbook 2013 residential cooling and heating load calculations procedure are also applied.

Fig. 1 Analysis room

2. System Description and Data Used

As illustrated in Fig. 1 a single room of Ege University’s mechanical engineering department building is chosen as a research area. Therefore, its basic properties that affect thermal load calculations, in a way of directly or indirectly, has to be determined. While envelope materials, doors and windows contribute directly, orientation of the building, color of the wall contributes indirectly. Their types and amounts are given below in Table 1. Also main geometric properties width, length, height and volume are measured as 3.11 m$^2$, 4.93 m$^2$, 3.85 m$^2$ and 54.01 m$^3$ respectively. In Table 1 thickness
values of window and door are not given because their total heat transfer coefficient values are taken from product catalogues.

![Table 1. Room properties](image)

Another essential factor that affects thermal load calculations is internal heat gains. These loads are determined as 460 W for four persons, 32 W for 8 fluorescent lighting, 115 W for a water dispenser and 100 W for a television. Lastly atmospheric conditions are taken for the city of İzmir differently based on each method’s calculation procedure.

3. Methods

In this study, four different methods are carried out for determining the capacity of a split type air conditioner unit in a single room of Ege University’s mechanical engineering department building. The methods considered include (i) a Turkish Standard (TS) 825 simulation program, that is quite popular in Turkey, (ii) a marketplace calculation tool, (iii) an Open Studio program based on Energy Plus and (iv) ASHRAE Handbook 2013 residential cooling and heating load calculations procedure.
TS 825 simulation program enables user to calculate specific heat loss calculation in other words heat capacity of HVAC system which can be defined as difference between heat losses (due to conduction, convection, ventilation) and heat gains due to solar radiation and internal loads such as occupants, hot water systems, cooking process, lightning and electrical appliances. When the program is run, one has to choose city name, net room height, ventilation type in terms of mechanical or natural and energy utilization type; normal (residential and educational buildings, standard office buildings) or high (cooking factories) in the first step. Secondly, material type and thickness amount of building envelope has to be entered to the program considering exposure envelope types which are given as open to the ambient, adjacent to unconditioned zone and adjacent to the ground. Then, material type and thickness amount of building envelope has to be entered to the program considering exposure envelope types which are given as open to the ambient or adjacent to unconditioned zone. Finally, area and direction properties of each window have to be entered to the program for calculating solar heat gain amount. After making these data entering procedure one can get specific heat loss, annual heating energy and lots of cross-section displays [3].

Marketplace calculation tool enables user to calculate cooling and heating capacities of HVAC unit under lots of assumptions made. So, just AutoCAD file of a room and its orientation information is enough for making these calculations.

Open Studio program based on Energy Plus enables user to calculate annual energy consumption performance, sizing of HVAC systems and building envelope, shading, lightening and ventilation analysis of the handled building. In this part, Ege University’s mechanical engineering department building is modelled by using Sketch Up 3D drawing program as shown in Fig. 2 on the left and then Open Studio program is run.

![Fig. 2 Sketch Up 3D Model](image)

Firstly, types of rooms (cafeteria, classroom, corridor, meeting room, office room, etc.), thermal zones and measurement parameters are described to the program with “Open Studio Inspector”. For example, a single room which thermal load calculations are carried out is defined as a meeting room illustrated in Fig.2 on the right side. Secondly, climatic zone information has to be given to the program which is defined by ASHRAE and it is 3C-warm seaside for İzmir. Secondly, material type and thickness amount of building envelope has to be entered to the program for calculating transmittance effects of the walls, ceiling and floor. Then, heat gains have to be identified as number of
people, lightening and electrical appliances per space floor area. After then, energy simulation and HVAC sizing can be done by choosing HVAC type, indoor temperature, indoor humidity and air velocity values. After these processes, instantaneous peak heating and cooling loads can be seen in result tables of the program with a name of Annual and Peak Values – Other.

ASHRAE Handbook 2013 residential cooling and heating load calculations procedure based on load factor method. In this method, indoor conditions are regarded as 24°C dry air temperature and 55% relative humidity in cooling mode; 20°C dry air temperature and 30% relative humidity in heating mode. Also outside dry air temperature values are taken as -2.8°C dry bulb temperature in heating mode and 35.8°C dry air temperature and 21.4°C wet bulb temperature in cooling mode. Wind velocity is assumed 3.4m/s. After these assumptions made, heat gains from opaque surfaces, transparent windows, ventilation, infiltration and internal loads are calculated using equations given below [4]. Heat gains from external walls, ceiling, floor and door can be calculated by (1) and (2). In these equations the symbols and their units are $q_{opq}$: heat gains from opaque surface (W), $A$: net surface area ($m^2$), $CF_{opq}$: surface cooling factor ($W/m^2$), $U$: total heat transfer coefficient of a construction material ($W/m^2K$), $\Delta T$: temperature difference (K), $OF_t$, $OF_b$, $OF_r$: opaque surface cooling factors and $DR$: cooling daily range (K), respectively. Note that, temperature of the unconditioned mediums are regarded as 3°C lower than the outside temperature.

\[
q_{opq} = A \times CF_{opq}, \tag{1}
\]
\[
CF_{opq} = U(OF_t \Delta T + OF_b + OF_r DR), \tag{2}
\]

Area of each external surface are given in table 1 and opaque surface cooling factors can be taken based on wall type [4]. Also daily range is calculated as 9K for İzmir. U values of each surfaces have to be evaluated for different constituents and their layers’ thickness values by using (3), (4) and (5) given below. In these equations the symbols and their units are $R$: thermal resistance ($m^2K/W$), $x$: thickness (m), $k$: thermal conductivity ($W/m K$), respectively. Also subscripts are o: outside air layer, i: inside air layer and 1,2,3,...,n represents each material of the wall. All values can be taken from appropriate tables [5].

\[
R_{wall} = R_1 + R_2 + R_3 + \ldots + R_n = \frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_3}{k_3} + \ldots + \frac{x_n}{k_n}, \tag{3}
\]
\[
R_{total} = R_o + R_{wall} + R_i, \tag{4}
\]
\[
U_{total} = \frac{1}{R_{total}}. \tag{5}
\]

After applying calculation steps given above heat gains from opaque surfaces can be found in Table 2.
Table 2. Heat gains from opaque surfaces

<table>
<thead>
<tr>
<th>No</th>
<th>Direction</th>
<th>Constituent</th>
<th>OFₜ</th>
<th>OFₛ</th>
<th>OFₑ</th>
<th>U</th>
<th>qₒpsq</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>West – open to the ambient</td>
<td>Wall</td>
<td>1</td>
<td>8.2</td>
<td>-0.36</td>
<td>9,150</td>
<td>39,898</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Column</td>
<td>1</td>
<td>8.2</td>
<td>-0.36</td>
<td>20,028</td>
<td>29,842</td>
</tr>
<tr>
<td>2</td>
<td>North and east – adjacent to unconditioned zone</td>
<td>Wall</td>
<td>1</td>
<td>0</td>
<td>-0.36</td>
<td>6,293</td>
<td>112,919</td>
</tr>
<tr>
<td>3</td>
<td>South - adjacent to unconditioned zone</td>
<td>Wall</td>
<td>1</td>
<td>0</td>
<td>-0.36</td>
<td>2,029</td>
<td>60,707</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Door</td>
<td>1</td>
<td>0</td>
<td>-0.36</td>
<td>4,870</td>
<td>9,448</td>
</tr>
<tr>
<td>4</td>
<td>Up</td>
<td>Deck roof</td>
<td>1</td>
<td>4.49</td>
<td>-0.36</td>
<td>3,510</td>
<td>18,535</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Suspended roof</td>
<td>0.62</td>
<td>-0.21</td>
<td>-0.19</td>
<td>0,868</td>
<td>8,757</td>
</tr>
<tr>
<td>5</td>
<td>Down</td>
<td>Floor</td>
<td>0.33</td>
<td>0</td>
<td>-0.28</td>
<td>0,283</td>
<td>4,352</td>
</tr>
</tbody>
</table>

Heat gains from fenestration can be calculated from (6), (7), (8) and (9). In these equations the symbols and their units are

- \( q_{\text{fen}} \): heat gain from fenestration (W), \( A \) : total window and frame area perpendicular to the heat transfer direction (m²), \( C_{F_{\text{fen}}} \) : cooling factor of transparent fenestration (W/m²), \( PXI \) : peak exterior irradiance, including shading modifications (W/m²), \( SHGC \) : solar heat gain coefficient, \( IAC \) : interior shading attenuation coefficient, \( FFs \) : fenestration solar load factor, \( T_x \) : transmission of exterior attachment, \( E_t \) : peak total irradiance (W/m²), \( F_{cl} \) : shade fraction closed, \( IAC_{cl} \) : interior attenuation coefficient of fully closed configuration, respectively.

\[
q_{\text{fen}} = A * C_{F_{\text{fen}}},
\]

\[
C_{F_{\text{fen}}} = U(\Delta T - 0.46DR) + PXI * SHGC * IAC * FF_s,
\]

\[
PXI = T_x * E_t,
\]

\[
IAC = 1 + F_{cl}(IAC_{cl} - 1),
\]

When \( U \), \( T_x \) and \( SHGC \) values are taken from product catalogue [6] and rest of symbols \( E_t \), \( F_{cl} \), and \( IAC_{cl} \) are taken from appropriate tables [4], \( q_{\text{fen}} \) can be found 1763.45 W.

Natural ventilation and infiltration occurs due to pressure difference between two mediums based on wind and temperature difference effects. On the other hand, mechanical ventilation occurs consciously by a HVAC design. While ventilation is essential for providing indoor air quality, infiltration causes by technical faults of a building envelope. Both ventilation and infiltration create heat gains and can be calculated as following equations [7].

\[
q_s = C_s Q\Delta T,
\]

\[
q_l = C_l Q\Delta W,
\]

Because of outside air temperature is always higher than inside room air in cooling mode, both sensible heat transfer (10) and latent heat transfer (11) affects are regarded as heat gains. In these equations symbols and their units are \( q_s \), \( q_l \) : cooling load caused by sensible and latent heat (W), \( C_s \), \( C_l \) : sensible and latent heat factors of air (W/LsK),
Q: volumetric flow rate (L / s), \( \Delta T \): temperature difference between outside and inside air (K), \( \Delta W \): air humidity ratio difference between outside and inside air (kg\(_w\)/kg\(_{da}\)), respectively. Both sensible and latent heat factors are calculated considering height of the room which is found 28m with an elevation of Izmir [8].

While ventilation heat gain calculation is carried out for a window, infiltration calculations are carried out for both window and door. For that reason, \( \Delta T \) and \( \Delta W \) values are calculated for window that open to the ambient and door that adjacent to unconditioned zone as 11.8 °C – 8.8 °C and 0.04 kgw/kg\(_{da}\) – 0.89 kgw/kg\(_{da}\), respectively. As one can see from (10) and (11) volumetric flow rates of each conditions has to be calculated.

In this study, ventilation is calculated in the case of open windows by using (12) given below. In this equation symbols and their units are \( Q_v \): fresh air volumetric flow rate (L/s), \( R_p \): required fresh air amount per person (L/s), \( P_z \): number of person, \( R_a \): required fresh air per unit area (L/s) and \( A_z \): conditioned floor area (m\(^2\)), respectively. When room properties and ASHRAE 62.1 standard values [9] for required fresh air amounts are used fresh air volumetric flow rate can be calculated as 14.608 L/s.

\[
Q_v = R_p \times P_z + R_a \times A_z , \tag{12}
\]

Infiltration is calculated in case of close door and windows by using (13) and (14) given below. In these equation symbols and their units are \( Q_i \): infiltration flow rate (L/s) \( A_L \): building effective leakage area (cm\(^2\)), \( A_{es} \): building exposed surface area, (m\(^2\)), \( A_{ul} \): unit leakage area (cm\(^2\)/m\(^2\)), and IDF: infiltration driving force (L/scm\(^2\)), respectively. All values can be found in tables [10] and when they are substituted in (13) and (14) infiltration volumetric flow rate of windows and door can be calculated 1.935 L/s and 0.233 L/s respectively. Then cooling load caused by sensible and latent heat gains can be calculated by using volumetric flow rates amounts. Their corresponding values are 211.15 W, 27.97 W and 2.51 W for sensible heat gain caused by ventilation open windows, infiltration closed windows and infiltration close door, respectively. For latent heat gain amounts values are 1.75 W, 0.23 W and 0.69 W, respectively.

\[
Q_i = A_L \times IDF , \tag{13}
\]

\[
A_L = A_{es} \times A_{ul} , \tag{14}
\]

Internal heat gains can be calculated by using (15) and (16). In these equation symbols and their units are \( q_{in,s} \) and \( q_{in,l} \): sensible and latent heat gain (W), \( A_{cf} \): room floor area (m\(^2\)) and \( N_{oc} \): number of occupants. All values are given in system description and data used section. When they are substituted in (15) and (16), sensible and latent heat gain amounts can be found 257.79 W and 111.37 W, respectively.

\[
q_{in,s} = 136 + 2.2A_{cf} + 22N_{oc} , \tag{15}
\]

\[
q_{in,l} = 20 + 0.22A_{cf} + 22N_{oc} , \tag{16}
\]
In heating load calculations procedure internal and solar heat gains are ignored due to their positive contribution. Ventilation and infiltration heat losses can be calculated using the same (10), (12), (13) and (14) equations steps without considering latent heat effects (11). Their values are 408 W for windows open ventilation, 105.05 W for windows closed infiltration and 14.92 W for door closed infiltration. But, heat gains from building envelope turns into heat losses and can be calculated by using (17) and (18). In these equation symbols and their units are $q_{\text{loss}}$: heat losses from building envelope (W), $A$: surface area of each surfaces (m$^2$), $HF$: heating load factor (W/m$^2$), $U$: total heat transfer coefficient (W/m$^2$K) and $\Delta T$: temperature differences (K), respectively.

\[
q_{\text{loss}}=A*HF, \quad (17)
\]
\[
HF=U*\Delta T, \quad (18)
\]

$U$ values of each surfaces are calculated in cooling load procedure and $\Delta T$ can be found with given temperature values at the beginning of this section.

### Table 2. Heat losses from building envelope

<table>
<thead>
<tr>
<th>No</th>
<th>Direction</th>
<th>Constituent</th>
<th>HF</th>
<th>$q_{\text{loss}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>West – open to the ambient</td>
<td>Wall</td>
<td>12.44</td>
<td>54.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Column</td>
<td>27.24</td>
<td>40.59</td>
</tr>
<tr>
<td>2</td>
<td>North and east – adjacent to unconditioned zone</td>
<td>Wall</td>
<td>22.41</td>
<td>402.12</td>
</tr>
<tr>
<td>3</td>
<td>South - adjacent to unconditioned zone</td>
<td>Wall</td>
<td>7.22</td>
<td>216.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Door</td>
<td>17.34</td>
<td>33.64</td>
</tr>
<tr>
<td>4</td>
<td>Up</td>
<td>Deck roof</td>
<td>6.13</td>
<td>32.38</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Suspended roof</td>
<td>3.67</td>
<td>37.00</td>
</tr>
</tbody>
</table>

Distinctly from cooling load calculations heat losses from floor is calculated with different equations given below. In these equation symbols and their units are $q_{\text{loss,f}}$: heat loss from the floor (W), $p$: heat loss per perimeter (W/mK), $HF$: heating load factor (W/m), $F_p$: floor perimeter length (m) and $\Delta T$: temperature difference (K), respectively. Heat loss from the floor can be easily calculated by using values given in this section and its value is 299.01 W.

\[
q_{\text{loss,f}}=p*HF, \quad (19)
\]
\[
HF=F_p \Delta T, \quad (20)
\]
4. Results and Discussion

Turkish Standard (TS) 825 simulation program, that is quite popular in Turkey enables to user just making overall heating load calculation. So, sizing a HVAC unit cannot be done. In this program, outside air temperature is regarded 12.22°C for the city of Izmir by using last twenty years’ October to May average values. Indoor air temperature is assumed 20°C. Heat gain amount is calculated with 0.32*V_{brut}*5 equation for educational buildings and it is 80W with a volume of 54.01 m³. Solar heat gain is evaluated as direct gain from windows and it is found 190.42 W October to May average value. Heat losses due to ventilation is calculated via 0.33*n_h*V_{brut} equation using n_h (ventilation number) is 0.8 for natural ventilation. Also gain utilization factor is defined scope of this program which decreases internal and solar heat gain amounts as a precaution of heating performance of a system.

In the marketplace calculation tool outside dry bulb and wet bulb temperatures are regarded 38°C and 25°C, respectively. On the other hand, comfort parameters for inside air conditions are taken 26°C dry bulb temperature and 50% relative humidity. Besides, 2 occupants and 130 kcal/h heat gain per an occupant assumption made in a room and lightening heat gain is assumed 10 kcal/h. Infiltration and ventilation effects are also considered in cooling load estimation. On the other hand, temperature values of outside air and inside air are taken 22 °C and 0°C respectively. While, Heat losses from building envelope and windows are calculated, internal, lightening, infiltration and ventilation heat gains are ignored in heating load calculation procedure.

In Open Studio program based on Energy Plus Open Studio, firstly 3D model has to be created and thermal zones have to be entered. In this study a single room is defined with other 11 thermal zones and it is called “project room”. Also more than 1000s surface and total 2531.75 m² area is researched by this program. Secondly, “IZMIR - TUR IWEC Data WMO#=172180” weather data is taken from official web site of Open Studio. When weather data analysis is carried out, the highest and lowest temperatures are obtained 36.20°C and -1.8°C, respectively. Then, only thickness value of building envelope materials is entered to the program and heat gain and heat losses caused by these materials can be calculated. Finally, occupants, lightening and electrical appliances heat gains are defined as intensity.

ASHRAE Handbook 2013 residential cooling and heating load calculations procedure is the most sensitive method with using 20 different equations as described above. By this method ventilation amounts and corresponding required window opening time van be presented. After using methods and basic properties discussion of four different calculation procedures, their calculation results and main advantages/disadvantages are given with Table 3.
Table 3. Comparison of calculation procedures

<table>
<thead>
<tr>
<th></th>
<th>TS 825</th>
<th>Marketplace</th>
<th>Open Studio</th>
<th>ASHRAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling load</td>
<td>Only cooling load can be calculated</td>
<td>2.56 kW (peak)</td>
<td>1.29 kW (peak)</td>
<td>2.58 kW (peak)</td>
</tr>
<tr>
<td>Heating load</td>
<td>0.456 kW (average)</td>
<td>3.35 kW (peak)</td>
<td>2.17 kW (peak)</td>
<td>1.86 kW (peak)</td>
</tr>
<tr>
<td>Advantages</td>
<td>Ventilation heat losses and internal heat gains can be calculated by giving height and volume of the room and ventilation type</td>
<td>Only requires AutoCAD file and orientation of the building</td>
<td>Detailed result analysis such as annual energy performance, shading analysis, etc.</td>
<td>Detailed total heat transfer coefficient calculation</td>
</tr>
<tr>
<td></td>
<td>Total heat transfer coefficient can be calculated with a rich library</td>
<td>Peak heating and cooling load can be calculated</td>
<td>Internal heat gains can be calculated in detail</td>
<td>Detailed ventilation and infiltration calculation</td>
</tr>
<tr>
<td></td>
<td>Heating energy utilization on a monthly basis</td>
<td>Ventilation, infiltration and internal heat gains can be calculated</td>
<td>Total heat transfer coefficient can be calculated with a rich library</td>
<td>Detailed solar heat gain calculation with considering curtain effect, daily range, etc</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Only average heat load can be calculated</td>
<td>Dependent to market assumptions</td>
<td>Drawing 3D model imperativeness</td>
<td>Using 20 different equations</td>
</tr>
<tr>
<td></td>
<td>Internal heat gains are constant and changes with a room area</td>
<td>Only volume of the room affects ventilation and infiltration calculations</td>
<td>Each thermal zones have to be defined</td>
<td>Lots of data input</td>
</tr>
<tr>
<td></td>
<td>Cooling load cannot be calculated</td>
<td>Outside air temperature is high</td>
<td>Difficulty in introducing HVAC system</td>
<td>If the outside temperature is less than 0°C, error in ventilation calculation</td>
</tr>
</tbody>
</table>

As a result, capacities of HVAC system has to be 2.585 kW (8820.385 BTU/h) for cooling and 3.35 kW (11430.673 BTU/h) for heating.
5. Conclusion Remarks

There are two main calculation procedure are applied in HVAC sector. This study is focused on instantaneous thermal load calculations which are used for HVAC sizing. This means the first step in energy consumption. If this calculation results are found more that the real value, it means more energy and could led to energy efficiency become almost meaningless. On the other hand, if this calculation results are found less than the real value, it means technical fault and led to unrealised comfort conditions. So, accurate and sensitive calculation procedure has to be used with a minimum assumptions made. ASHRAE Handbook 2013 residential cooling and heating load calculations procedure is the best option especially with opaque surface cooling factors, cooling daily range, fenestration solar load factor, thermal resistance of outside and inside air layers, etc. which make the calculation procedure more accurate.

Acknowledgment

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References