HEAT PUMPS
– The theory

Heat pumps are becoming increasingly popular amongst selfbuilders. As we shall see below, they give lower carbon emissions and lower running costs than gas or oil boilers. Unfortunately, the capital cost for installing a heat pump system is usually higher than for installing an oil boiler with storage tank, and much higher than for installing a gas boiler with connection to a nearby gas supply. However, as new houses become more energy efficient, heat pump systems for them become smaller and more affordable.

Supermarkets have BOGOF offers – Buy One Get One Free. The attraction of heat pumps is that they offer even more. With a heat pump, the promise is: Buy One (unit of electricity) Get Two Or Three Free.

Coefficient of Performance

In the natural world, heat flows from a higher temperature to a lower one. In contrast, a heat pump can capture heat from the cold surroundings outside a house and deliver it inside to make the house warmer. (Sometimes the heat is also used to heat the hot water.)

An electric radiant fire is 100% efficient. If 1 kWh of electricity is used by the fire it delivers 1 kWh of heat – it’s ‘Coefficient of Performance’ (COP) is 1. The marvel of a heat pump is that it delivers more heat energy than the electrical energy put into it. So if 1 kWh of electricity is put into a heat pump it might deliver, say, 3 kWh of heat, giving a COP of 3. The heat pump has extracted an extra 2 kWh of “free” heat from the surroundings outside the house – the ground, air or water – and delivered it inside. What’s more, the heat that has been extracted is renewable, so heat pumps can be considered to be, in the main, a renewable energy technology.

The carbon analysis

Last month’s article gave the carbon dioxide emissions resulting from the use of different fuels (taken from the draft version of SAP2009). Because modern gas and oil boilers have an overall (‘seasonal’) efficiency of about 85%, we can obtain:

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Kg of CO₂ per gross kWh</th>
<th>Kg of CO₂ per useful kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mains gas</td>
<td>0.206</td>
<td>0.242</td>
</tr>
<tr>
<td>Oil</td>
<td>0.284</td>
<td>0.334</td>
</tr>
<tr>
<td>Mains electricity –</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct heating</td>
<td>0.591</td>
<td>0.591</td>
</tr>
<tr>
<td>Heat pump, COP of 3</td>
<td></td>
<td>0.197</td>
</tr>
<tr>
<td>Heat pump, COP of 4</td>
<td></td>
<td>0.148</td>
</tr>
</tbody>
</table>

Carbon dioxide emissions for fossil fuels and electricity

The emissions figure for electricity is an average over the many diverse power sources that feed the grid, from coal fired (high emissions) to wind powered (zero
emissions). Ground source heat pumps usually have an overall COP between 3 and 4. For air source systems the overall COP is usually somewhat below 3.

From the figures above, direct electrical heating (e.g., by a radiant fire or an immersion heater) results in 2.4 times the carbon dioxide emissions using gas (or 1.9 times using oil). In short, direct heating with mains electricity is carbon intensive.

But a heat pump system operating with a COP of 3 cuts emissions by two thirds compared to direct electrical heating. From the figures above, a heat pump with a COP of 3 results in 19% lower emissions than gas (or 44% lower emissions than oil). If the COP were 4, the cuts in emissions would be correspondingly greater: 39% lower emissions than gas (or 56% lower than oil).

The carbon analysis is important because, as I mentioned last month, to get building regulations approval for a new house, the DER (Dwelling Emissions Rate) has to be below its TER (Target Emissions Rate). The draft version of SAP2009 has a reduced TER compared to that in the existing SAP2005. (The government’s intent is to progressively reduce the TER so that by 2016 all new housing will be zero carbon.)

The money analysis

Important as carbon emissions are in the building regulations’ Standard Assessment Procedure (SAP), the basis of SAP is the theoretical running costs for space and water heating, ventilation, and lighting in the house. For a high SAP rating, the running costs must be low.

Fuel costs are given in the draft SAP2009, from which we can derive the following table:

<table>
<thead>
<tr>
<th>Electricity</th>
<th>Pence per kWh</th>
<th>Pence per useful kWh</th>
<th>Standard tariff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity, on peak</td>
<td>11.8</td>
<td>Also 11.8</td>
<td>Economy 10</td>
</tr>
<tr>
<td>Electricity, off peak</td>
<td>6.5</td>
<td>Also 6.5</td>
<td>Economy 10</td>
</tr>
<tr>
<td>Gas</td>
<td>2.8</td>
<td>3.3</td>
<td>Standing charge £98</td>
</tr>
<tr>
<td>Oil</td>
<td>4.0</td>
<td>4.7</td>
<td>85% efficiency</td>
</tr>
</tbody>
</table>

Fuel costs

(With a typical 10-hour tariff, the off-peak charge applies for 5 hours in the night, 3 hours in the afternoon, and 2 hours in the evening.)

SAP specifies that for a heat pump on a 10-hour tariff the on-peak electricity accounts for 60% of the total. This seems too high to me. Installing Under Floor Heating (UFH) in a concrete screed gives high thermal inertia, so more use could be made of off-peak electricity. But anyway, using the SAP figure (60%) we obtain the average cost of 1 kWh of electricity to be 9.7p. With a COP of 3, the cost of 1 kWh of heat supplied by the heat pump would be 3.2 pence – much the same as the cost of using gas (3.3p). But if we take into account the standing charge for gas and the cost of annual maintenance of a gas boiler – no maintenance for a heat pump – then the heat pump system is likely to have a somewhat lower running cost. (More decisively, the heat pump system has a 32% lower running cost than oil – or even lower when maintenance costs of the boiler are included.)
If the COP were 4, the savings on fuel costs would be greater: 27% less than gas, and a decisive 48% less than oil.

And if, as I believe, with UFH in a screed the heat pump could operate most of the time with off-peak electricity, the money savings above would be even higher – by as much as 49% higher if the pump operated only with off-peak electricity.

These are all hypothetical figures, of course, but some figures are better than none.

**How a heat pump works**

We’re familiar with the fact that a gas gets warm when it is compressed – a bicycle pump gets warm in use. And conversely a gas cools down when it expands, as shown by the cooling of the nozzle when bottled gas is released.

The workings of a domestic heat pump are based on a ‘vapour compression cycle’ in which a fluid (the refrigerant) is forced continuously round a closed circuit. The refrigerant is chosen to have a suitable boiling point so that in parts of the circuit the fluid is a gas and in other parts a liquid.

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![Diagram of a Ground Source Heat Pump](image)

**Diagram of a Ground Source Heat Pump**

*Supplying heat for Under Floor Heating.*

The four components of the circuit are:

- **Compressor**
  
  Electricity is used to compress the gaseous refrigerant and this becomes hot as a result of the compression (eg, pressure 15 bar, temperature 75ºC – see Footnote). The compressor also drives the fluid around the circuit.

- **Condenser**
  
  The output heat exchanger. The hot gas gives up its heat to water in a heat exchanger. As a result of cooling, the gas is condensed to a liquid, giving up its latent heat. The liquid is cooled further in the heat exchanger (eg, down to 40ºC) and more heat is transferred to water.
• **Expansion valve**  
The liquid refrigerant passes through a valve, and expands into the evaporator. Its pressure falls and consequentially its temperature drops (eg, to 2 bar, 0ºC).

• **Evaporator**  
The source heat exchanger. The cold, liquid refrigerant absorbs heat from the heat source and evaporates.  
Then the gaseous refrigerant carries this heat to the compressor, where the cycle starts again.

**The theory of the perfect heat pump**

If you want to cut through some of the hype which is to be found in the growing heat pump industry – mostly from the johnny-come-latelies – then it helps to understand some of the theory of heat pumps.

The process was initially described in the Nineteenth century by a French physicist, Carnot, and a little later the mathematical theory of the ‘Carnot cycle’ was worked out. This gives, for the perfect heat pump:

\[ \text{Coefficient of Performance, } COP = \frac{T_1}{T_1 - T_0} \]

where \( T_1 \) is the final (output) temperature, and \( T_0 \) the initial (source) temperature.

However, the temperatures have to be expressed as absolute temperatures. Some readers may know that a temperature colder than –273 ºC is not possible.

Temperatures can be measured from this absolute zero, and expressed in kelvins (K). For example, the temperature at which water freezes can be expressed as either 0ºC or 273K. (The name honours the British physicist, Lord Kelvin.)

For a perfect heat pump, pumping heat from a temperature of 0ºC (273K) to 35ºC (308K) – eg, for UFH – we have:

\[ \text{COP} = \frac{308}{308 - 273} = \frac{308}{35} = 8.8. \]

(Note that the COP’s of real world heat pumps are very roughly about half the theoretical values.)

**Variation of COP with output temperature**

Say that our perfect heat pump is raising the temperature not to 35ºC but to 60ºC (333K), eg, for Domestic Hot Water.

Then:

\[ \text{COP} = \frac{333}{333 - 273} = \frac{333}{60} = 5.6. \]

Increasing the output temperature to 60ºC has resulted in the COP being reduced from 8.8 to 5.6 – a large drop in performance. Expressed another way, the heat pump requires 57% more electricity to raise the water temperature to 60ºC rather than 35ºC. Radiator systems use water at temperatures higher than 60ºC. So if you intend to install a heat pump, match it with UFH rather than radiators.
Variation of COP with source temperature

COP also varies with the source temperature, and this variation is particularly significant for air source systems because air temperatures are more variable than ground temperatures.

If our output temperature is 35°C (or 308K), then using the equation above we can obtain:

<table>
<thead>
<tr>
<th>Outside air temperature</th>
<th>Coefficient of Performance COP</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>K</td>
</tr>
<tr>
<td>-5</td>
<td>268</td>
</tr>
<tr>
<td>0</td>
<td>273</td>
</tr>
<tr>
<td>5</td>
<td>278</td>
</tr>
<tr>
<td>10</td>
<td>283</td>
</tr>
<tr>
<td>15</td>
<td>288</td>
</tr>
</tbody>
</table>

Variation of COP with source temperature

The table shows why the overall COP of an air source heat pump is likely to be lower than that for a ground source system. On a cold winter’s day, when there is the most demand for heat, the COP of an air source system is relatively low. In contrast, temperatures underground are steadier and warmer, so the COP of a ground source system is higher.

Next month: More about heat pump systems.

FOOTNOTE – The 'bar', a unit of pressure

One bar is the pressure of ten Newtons per square centimetre. I like to remember the Newton as the force due to the weight of a small apple – which is said to have fallen on Newton’s head! (9.81 Newton = weight of 1 kg.)

One bar is also approximately the atmospheric pressure at sea level.

The word is derived from the Greek, βάρος, pronounced like 'baros' and meaning 'weight'.

Words: 1830.