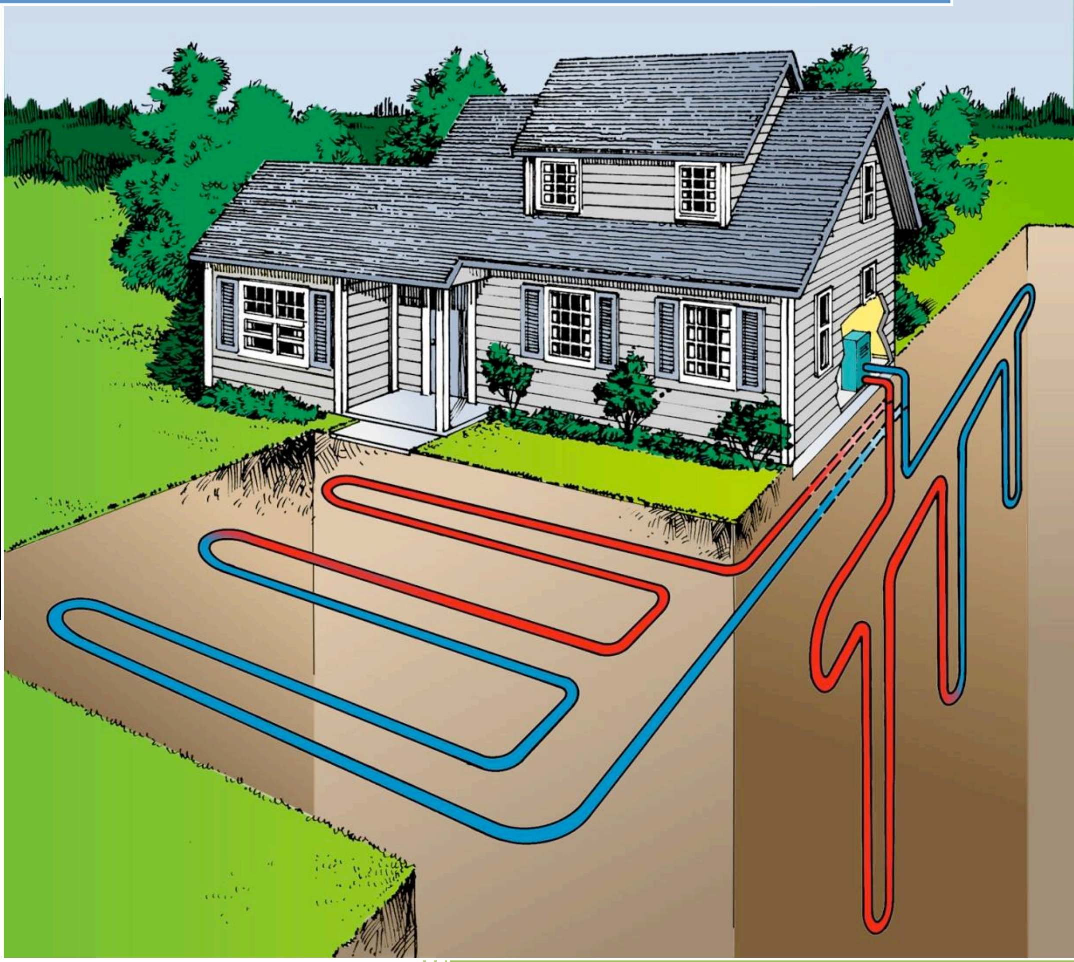
2011

The Science behind a Ground Source Heat Pump



A description of the operation of a ground source heat pump written for the Kanata Environmental Network

AUTHORS: Christophe SIEWECKE,
Khan Rafat ISLAM,
Sahil KAZI,
Mohammed ZABER

Undergraduate students, Carleton University, Faculty of Engineering & Design

Carleton UNIVERSITY

Edited by Christophe SIEWECKE

June 20th, 2011

The Science behind a Ground Source Heat Pump

Summary

A Ground Source Heat Pump (GSHP) is a heating system which uses stored heat energy from the ground to heat a building. Solar energy travels from the sun to the earth in the form of radiation and, on average, 46% of this energy is absorbed by the ground. The evaporator in the GSHP absorbs this heat which is then transferred throughout the GSHP via the refrigerant. A refrigerant is a fluid that transfers heat from the ground to the building, in the form of latent energy, by changing its phase from liquid to gas. The compressor then pumps this gas, increasing its pressure and temperature, into the condenser. The condenser is located inside the building. When the gas reaches the condenser, it releases the latent energy to warm the building. It becomes condensed and is then passed in to the expansion valve where its pressure is reduced and then circulated back into the evaporator to carry on the cycle.

1.0 Introduction

The purpose of this document is to describe the operation of a ground source heat pump (GSHP) by explaining the function of its four primary components.

This document was assembled by a team of undergraduate engineering students from Carleton University, and we are:

Kahn Rafat ISLAM
Sahil KAZI
Christophe SIEWECKE
Mohammed ZABER

The client for whom this document has been assembled is the Kanata Environmental Network (KEN). KEN is a volunteer-run organization in the community of Kanata. They: "share information about practical, ecologically-friendly solutions with Kanata residents, and work towards a green and healthy future for all [1]."

This document will consist of a product description split into six sections. Section 2.0 consists of an overview of the whole GSHP system, as well as an explanation of where the *energy* in a GSHP comes from. Next, section 2.3 deals with the *refrigerant* used in the GSHP and how to choose it. Section 3.1 contains a description of the function of the evaporator. In section 3.2 there is an explanation of how the compressor operates, followed by section 3.3 which covers the function of the evaporator. Finally, section 3.4 consists of a description of how the expansion valve operates, and how it is used in the GSHP.

A glossary is included at the end of this document. All terms which can be found in the glossary appear in italics throughout the document.

2.0 System Overview

In this section, a system overview of the GSHP will be presented. First a general description of the system will be given, followed by an explanation of where the *energy* for a GSHP comes from.

2.1 General Description

In Fig. 1 below we see an example of what is called a *direct expansion GSHP*. The compressor pumps gaseous refrigerant from the ground through the house where the refrigerant becomes a liquid which then flows back to the ground where it becomes a gas. This is the type of system we will be looking at throughout this document. Such systems can be configured to both heat and cool a house; we will focus only on the heating cycle of such a system*.

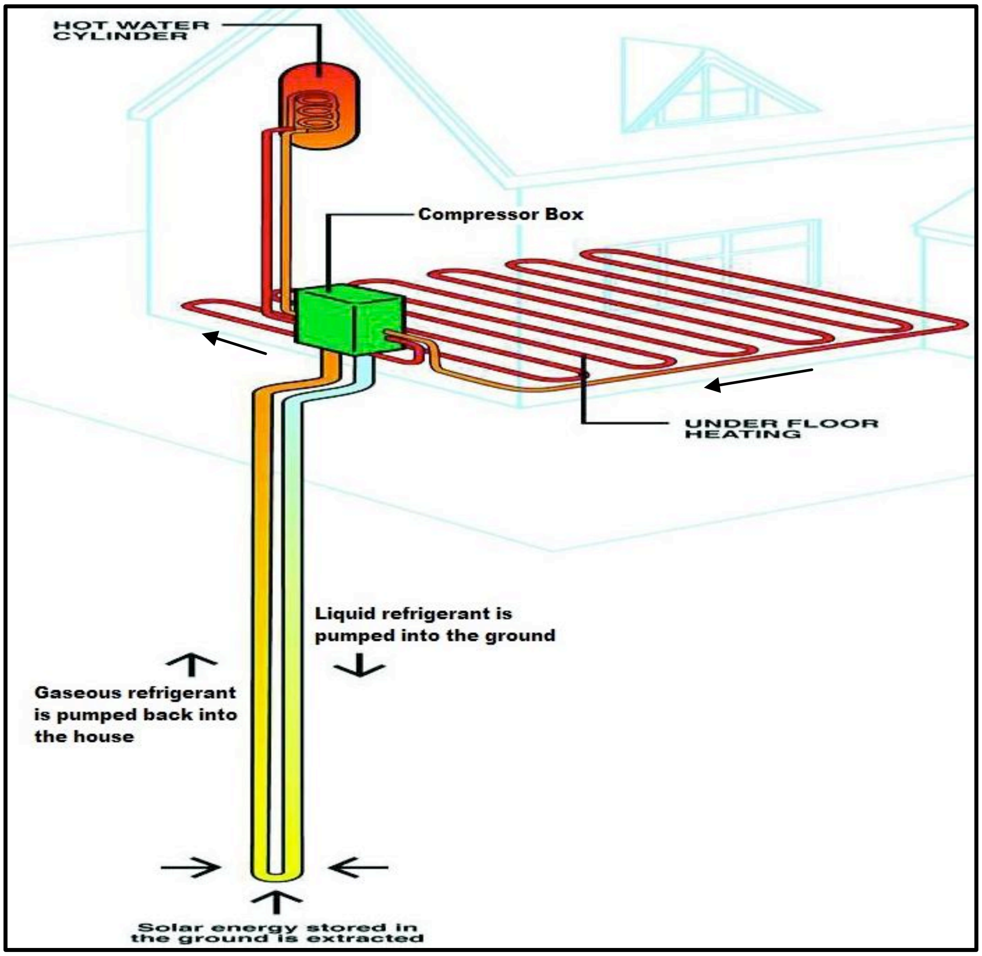


Figure 1. System Diagram [2, modified]

*Visit this website for more information concerning using a GSHP to cool:
http://oee.nrcan.gc.ca/publications/infosource/pub/home/Heating_and_Cooling_with_a_Heat_Pump_Section4.cfm

The heat pump cycle shown below in Fig. 2 is the cycle that is used by a GSHP to heat a house. The compressor is what pumps the working fluid from the evaporator to the condenser and back again. The four primary components (evaporator, compressor, condenser, expansion valve) of this cycle will be looked at in detail in section 3.0.

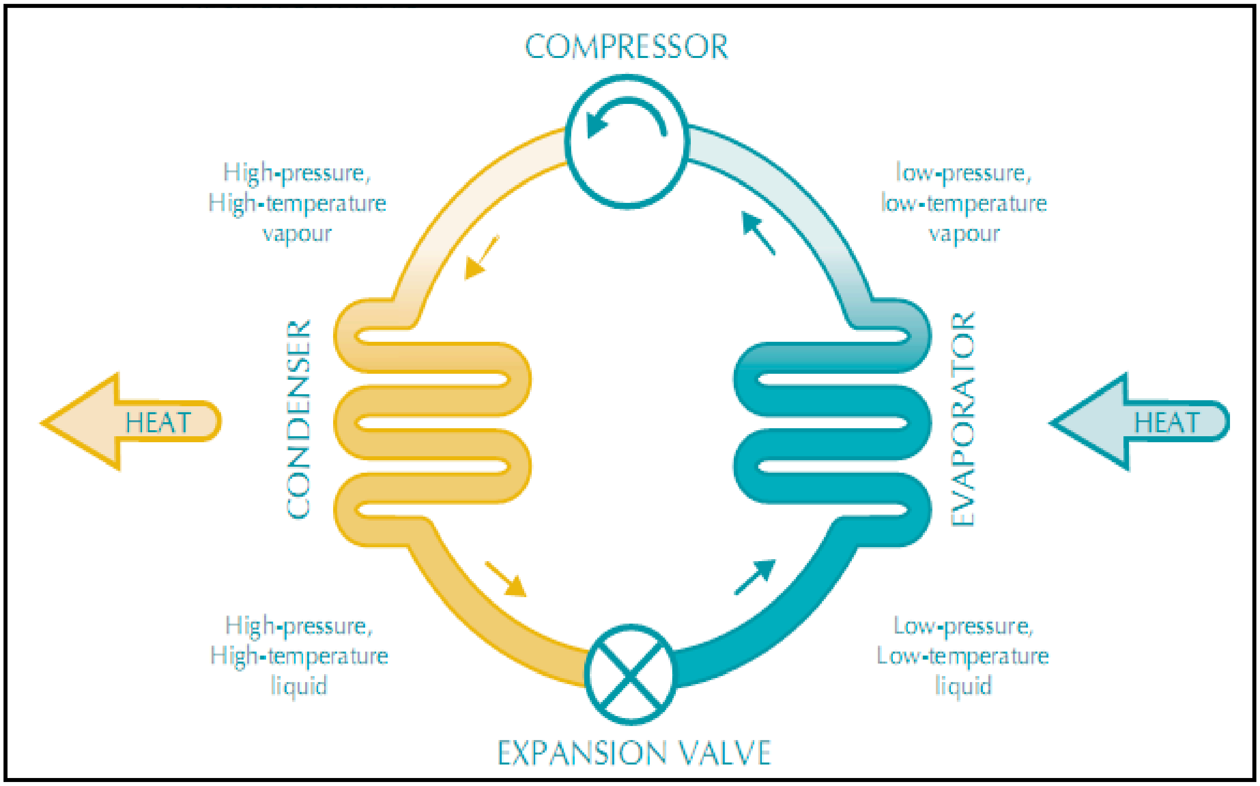


Figure 2. Heat pump cycle [3, modified]

2.2 Energy Source: the Sun

The sun is the main source of *energy* for the ground source heat pump. Below we will discuss *heat* transfer from the sun to Earth, radiation and how much of this radiation is absorbed by the ground and what the determining factors of this absorption are.

The sun is mainly made up of hydrogen [4]. This hydrogen is then transformed into helium by *nuclear fusion* and it is due to this that *heat* is emitted from the sun. This *heat energy* then reaches Earth by the process known as radiation.

Radiation transfers *energy* from one source to another through the medium of space [5]. This transfer is done via *electromagnetic waves* [6]. When the radiation reaches the earth, before reaching the ground the radiation has to pass through the atmosphere, the *ozone layer*, the clouds, water vapour, etc. [3]. Some of the radiation is also reflected back into space. On average 46% of the radiation from the Sun is absorbed by the ground [3].

Fig. 3 below shows the radiation distribution of the sun.

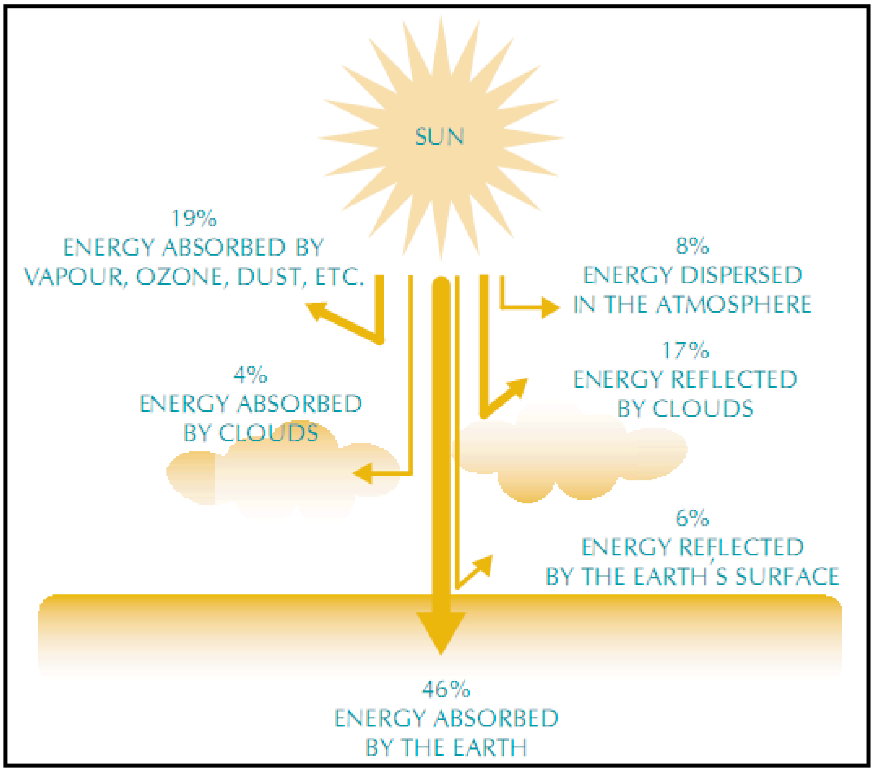


Figure 3. Radiation distribution [3]

The absorption of the radiation by the soil will depend on the water content of the soil, slope of the land, water content of the soil, vegetative cover etc. [7]. Thus, absorption will vary from place to place.

Now that we know the main source of *energy* for the Ground Source *Heat* Pump, we will discuss what transfers this energy from the ground to the building: the *refrigerant*.

2.3 The Refrigerant

This section will explain what a *refrigerant* is (2.3.1) and how it is chosen (2.3.2).

2.3.1 What is a Refrigerant?

The working fluid of a closed-loop *direct expansion GSHP* is a *refrigerant* [8]. *Refrigerant*s are used for both *heat*ing and cooling and are also known as anti-freeze. A *refrigerant* is any substance which is used to transfer *heat* from one point to another, often using the change of state from *gas* to *liquid* and vice-versa. In the past, most *refrigerant*s were *CFCs* (chlorofluorocarbons) and *HCFCs* (hydro-chlorofluorocarbons) [9]. These substances are quite effective and efficient *refrigerants* however they have severe environmental impacts, notably causing depletion of the *ozone layer*, as well as being very potent *greenhouse gases*. These substances are now banned and other more eco-friendly *refrigerants* must be used.

2.3.2 Choosing a Refrigerant

The choice of the *refrigerant* in a GSHP is a relatively complex process. It requires striking a delicate balance between performance efficiency, safety and environmental concerns [10]. One important performance criterion is the *normal boiling point* of the *refrigerant*. The *refrigerant* must boil at a *temperature* which is lower than the ground *temperature* for it to be useful in the GSHP. Another performance criterion is density. The higher the density, the higher the *energy* transferred by the *refrigerant*. One popular *refrigerant* is R-134a, because its *normal boiling point* is low enough to allow the system to function, and also because of its relatively high density (see Table 1 below). Since R-134a has a higher density than propane or isopentane, it transfers more *heat* per unit volume which increases its efficiency.

Table 1. Thermodynamic properties of some compounds used as refrigerants [11]

Name and Formula	Molecular Weight (g/mol)	Density (kg/m3)	Melting T (°C)	Boiling T (°C)	Heat of Vaporization (kJ/kg)	Constant P Heat Capacity (kJ/kg-K)
R134a $H_2FC\text{-}CF_3$	102.03	1206	−101	−26.6	215.9	0.853
Propane C_3H_8	44.096	582	−187.7	−42.1	425.31	1.701
Isopentane C_5H_{12}	72.15	626	−160	28	344.4	2.288

3.0 Product Description by Component

Now that we have discussed the source of heat energy in a GSHP (the sun), as well as the substance used to transport this heat throughout the system (the refrigerant), we will move on to the four primary components of the GSHP which play a vital role in its function. As shown in Fig. 2 (in section 2.1), the four components that we will discuss are the evaporator, the compressor, the condenser and the expansion valve.

3.1 The Evaporator

We will start with the evaporator; first we will discuss its location and function, then the principles behind its operation: *heat* absorption and latent *energy* during phase change.

3.1.1 Location and Function

The evaporator is underground tubing (refer to Fig. 1 in section 2.1). It is usually made of hollow metal pipes, which have good *thermal conductivity*. The transfer or energy in the *heat* pump cycle (refer to Fig. 2 in section 2.1) starts at the evaporator [3].

The *refrigerant* flows inside the evaporator. It is used to transfer *heat* energy to the house from the ground. When the evaporator absorbs this *heat energy*, it vaporizes the *refrigerant* which transforms the *refrigerant* from *liquid* to *gas.* This process is called evaporation. This *gas* is then compressed by the compressor and is circulated throughout the GSHP.

3.1.2 Heat Absorption

As mentioned in section 2.2 above, 46% of the sun's radiation is trapped by the ground. This *heat energy* from the ground is then absorbed by the evaporator.

The radiation from the sun is absorbed by the ground and it is then absorbed by the evaporator. The evaporator then transfers the *heat energy* to the *refrigerant* and the *refrigerant* changes from *liquid* to *gas*. Latent *energy* is then stored in the *gas* as will be explained in section 3.1.3 below.

3.1.3 Latent Energy during Phase Change

Any *substance* can take the form of or a combination of three phases: a *solid, liquid*, or *gas* [13]. A change in *chemical* and thus *physical properties* causes the *substance* to change phase. We can cause a change in *physical* or *chemical properties* by adding or removing *heat* from any *substance* [14].

The *heat* added or released which causes a change of state is called latent *heat* (or latent *energy*) [14]. Latent *energy* or latent *heat* is the *energy* which causes bonds between adjacent *molecules* of a substance to break. Bonds hold *molecules* of a substance together. The absorption of *energy* causes bonds to break, while the release of *energy* causes bonds to be formed.

Fig. 4 below illustrates the concept of latent *energy* during the phase change of water, which is analogous to the behaviour of the *refrigerant* used in the GSHP.

In Fig. 4, the y-axis represents the *temperature* and the x-axis represents the *energy* supplied. As we supply *energy* to the water, the *temperature* increases. When we reach part D, the *temperature* stops rising, but the *energy*, on the x-axis, keeps on increasing. This *energy* is the latent *energy* which is used to break the bonds between water *molecules* to change to *gas*.

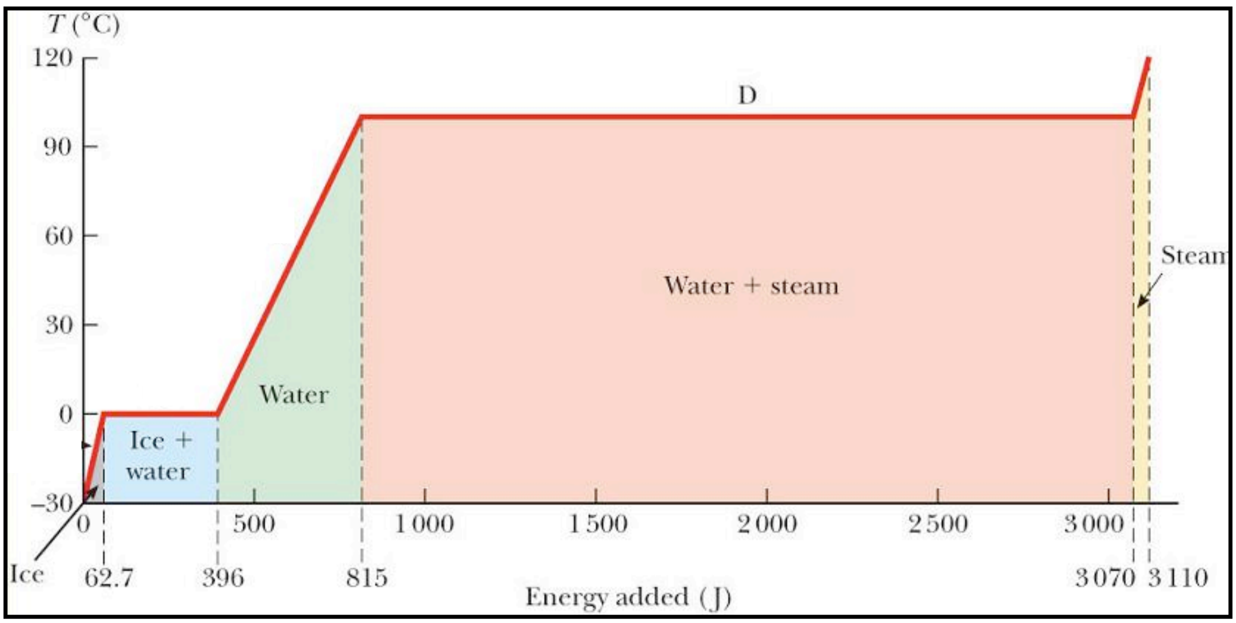


Figure 4. Latent energy and phase change of water [15, p. 13]

To summarize, the Evaporator absorbs *heat energy* from the ground, which is used to turn the *refrigerant* into a *gas*. In doing so, the *gas* stores this *energy* in the form of latent *energy*. It is then circulated throughout the GSHP using the compressor and this latent *energy* that is stored in the *gas* is then released in the house, via the condenser. These components will be more elaborately discussed in sections 3.2 and 3.3 below.

3.2 The Compressor

The purpose of this section is to describe the role and the working principles of the compressor. The compressor is what actually initiates the flow of *refrigerant* through the whole ground source *heat* pump (GSHP) when it pumps the *refrigerant* from the evaporator. A brief description of the compressor can be found in section 3.2.1, followed by an explanation of the working principles of the compressor in section 3.2.2.

3.2.1 About the Compressor

A compressor is a mechanical device that increases the pressure of a *gas* by reducing its volume. Compression of a *gas* naturally increases its *temperature* [16]. Fig. 5 shows what a compressor looks like.

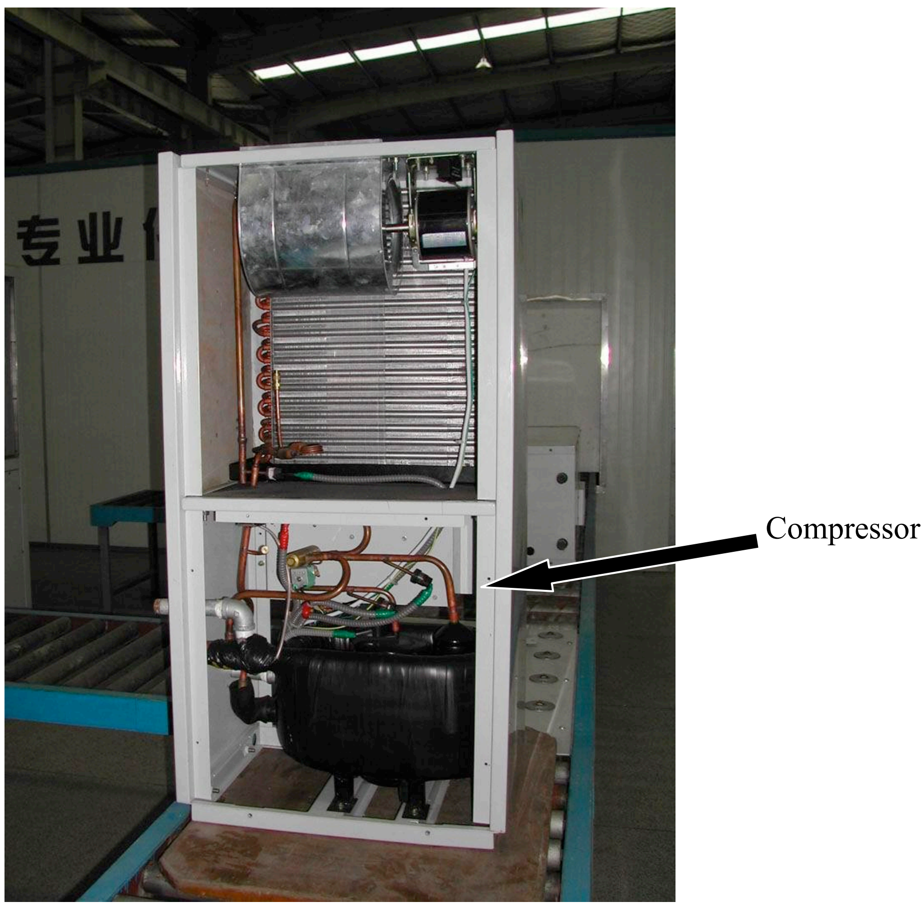


Figure 5. Compressor [17]

There are different types of *gas* compressors but the best suited one for a GSHP is called the reciprocating compressor [18]. It gives out *gas* at a high pressure and *temperature*. It has higher efficiency and it needs less electricity to run than other compressors.

The compressor has an inlet (see Fig. 6) where it takes *gas* in and an outlet where it releases the *gas*. The compressor is made of a strong metal such as stainless steel.

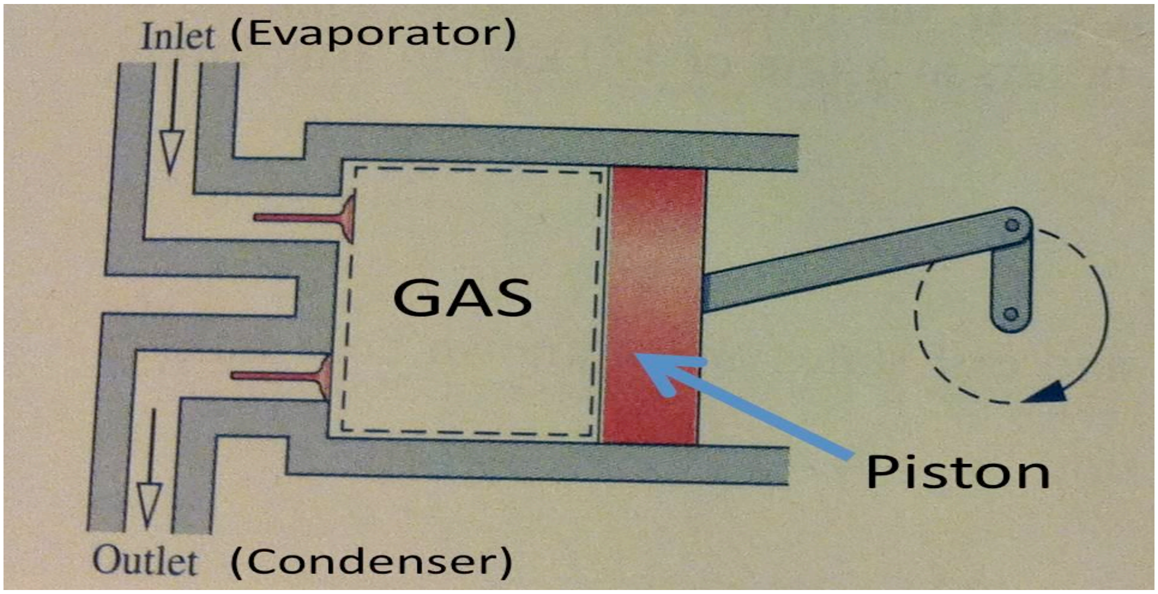


Figure 6. Schematic diagram of compressor [19, modified]

In the GSHP the inlet is connected to the evaporator and the outlet to the condenser (see Fig. 6). There is a *piston* that moves back and forth in the compressor. When the *piston* moves backwards, it sucks the *gas* from the evaporator. Since the *refrigerant* changes completely from *liquid* to *gas* in the evaporator, the compressor only takes *gas* from the evaporator. While the *piston* moves forward, the *gas* is compressed causing volume to decrease and pressure to increase [20]; this will be discussed more in section 3.2.2.2.

3.2.2 Working principles

The compressor uses the principles of pressure and conservation of energy to operate. These working principles of a compressor are discussed in sections 3.2.2.1 and 3.2.2.2.

3.2.2.1 Pressure

Pressure is defined as force per unit area, which is calculated by taking the total force and dividing it by the area over which the force acts [21]. The equation of pressure is given by Equation 1 below:

Eq. 1 $$\boldsymbol{P} = \frac{\boldsymbol{F}}{\boldsymbol{A}}$$ [21]

Where P is Pressure, F is the net force and A is the area over which the force is acting.

The *piston* is moving constantly due to a motor. When the *piston* moves forward inside the compressor the inlet closes and the outlet opens (see Fig. 6). The ideal *gas* law states: "Pressure is inversely proportional to volume for *gas* in a closed system and directly proportional to *temperature*" [22]. This explains why the pressure of *gas* inside compressor increases instantaneously with *temperature*. As the *piston* moves forward the *gas* compresses and the volume decreases which, in turn, increases pressure and *temperature* according to the ideal *gas* law.

A balloon can be used as a model to explain the compressor (see Fig. 7 below).

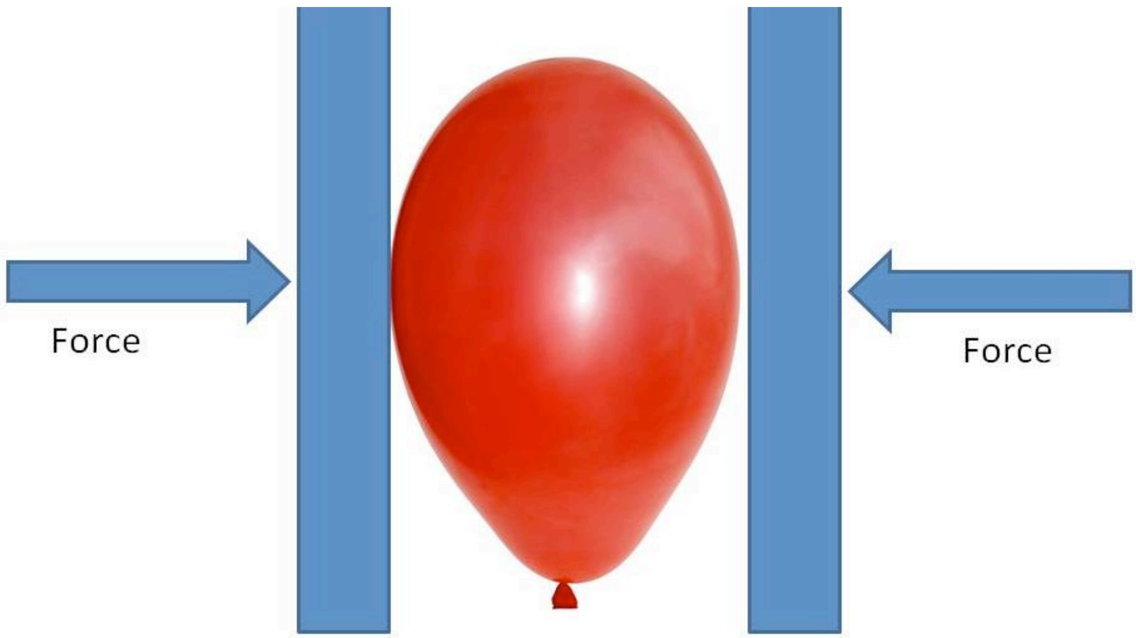


Figure 7. Analogy of a compressor [Mohammed Zaber]

If we take a balloon, fill it up with water, hold the balloon upside down and squeeze the balloon at the bottom, the water at the bottom will move upwards. This happens due to an external force being applied at the bottom of the balloon. The pressure inside the balloon increases which forces the water to move upwards. This is what happens in the compressor except that the *temperature* increases because the compression is much higher than that in the balloon.

3.2.2.2 Conservation of Energy:

According to the law of conservation of energy, *energy* in a system may take on various forms (e.g. *mechanical* and *heat*) [23]. The law of conservation of energy states that *energy* may neither be created nor destroyed. Therefore, the sum of all the energies in the system is a constant.

As shown in Fig. 3, the input of *electrical energy* to the compressor from the electrical source of the house is what starts the compressor. The *electrical energy* moves the *piston* back and forth in the compressor causing the *electrical energy* to be converted into *mechanical energy* [9]. When the *piston* moves backwards, it sucks the *gas* from the evaporator. Then the *piston* moves forward, the inlet closes and the *gas* compresses increasing the pressure and *temperature* (refer to Fig. 6). This increase in pressure and *temperature* cause the *mechanical energy* to be converted into *heat energy*.

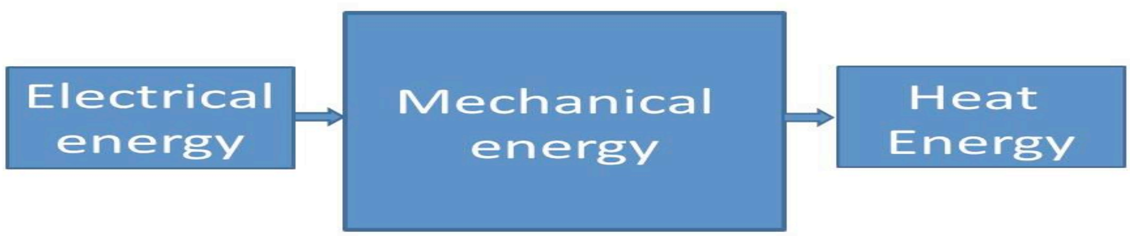


Figure 8. Conservation of energy [Mohammed Zaber]

The role of the compressor in the ground source *heat* pump is to increase the pressure of the *gas*eous *refrigerant*, which also causes the pressure of the *refrigerant* to rise. As we have seen, *electrical energy* transforms into *heat energy* in the compressor. The compressor also helps the *gas*eous *refrigerant* to maintain the flow in the GSHP. The hot *gas* is then pumped into the condenser which will be discussed in section 3.3.

3.3. The Condenser

3.3.1 Introduction to the Condenser

This section of the GSHP description consists of three principles which will be used to explain how *heat* is released from the *refrigerant* and circulated throughout a house via a condenser. The condenser is a radiator used to circulate *heat* throughout a room by condensing a substance from a *gas* to a *liquid* (see Fig. 9). To understand how the condenser releases *heat* from the *refrigerant* and circulates it throughout a house, the concepts of latent *energy* during phase change, the second law of thermodynamics, and the conservation of *energy* will be explained. Fig. 1 below is one example of a condenser which consists of coils underneath the floor that transfers *heat* to the cooler air above.

The high *temperature refrigerant* is pumped into the condenser by the compressor [24, p. 4].

Figure 9 – Hollow coils located beneath the floor [25]

3.3.2 Release of Latent Energy during Phase Change in the Condenser

An explanation of latent *energy* during phase change enables us to understand how *heat* is transferred from the *refrigerant* to the cooler air inside a room. Any *substance* can take the form of or a combination of three states: a *solid, liquid*, or *gas* [26]. A change in *chemical* and thus *physical properties* causes the *substance* to change state (or change phase). We can cause a change in *physical* or *chemical properties* by adding or removing *heat* from any *substance* [27].

The *heat* absorbed or released which causes a change of state is called latent *heat* (or latent *energy*) [28]. Latent *energy* or latent *heat* is the *energy* which causes bonds between adjacent *molecules* of a substance to break. Bonds hold adjacent *molecules* of a substance together. The absorption of *energy* causes bonds to break, while the release of *energy* causes bonds to be formed [27]. As a result, *heat* absorbed or removed in the form of latent *energy* causes no further increase in *temperature*, rather a change of phase [27]. For example, water begins to boil when the *temperature* of *liquid* water plateaus at 100 degrees Celsius [28]. The additional inflow of *heat* is used as *energy* to break bonds between adjacent water *molecules* rather than increase the *temperature* [29]. The release of latent *energy* is a result of phase change. Fig. 10 on the right illustrates the absorption of latent *energy* during evaporation and the release of latent *energy* during condensation. This process occurs inside the coils of the condenser (refer to Fig. 9).

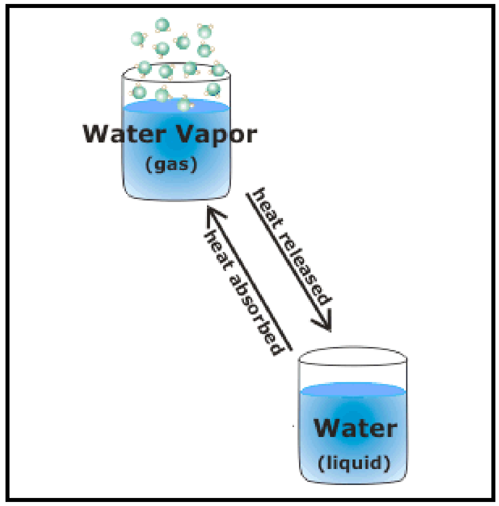


Figure 10 – Condensation of liquid water to water vapor [30]

In the condenser, latent *energy* is released as a result of phase change. The initiation of phase change via a condenser will be explained in section 3.3.3.

3.3.3 How Is Phase Change Initiated? (Second Law of Thermodynamics)

A *temperature* gradient is defined as a difference in *temperature* between two points. The second law of thermodynamics states that *heat* will always spontaneously flow from a point at a higher *temperature* to a point at a lower *temperature*[3][27]. For example, a cup of hot coffee will become cold over time if it is exposed to the cooler *temperature* of the atmosphere (as shown in Fig. 11). This is an example of the second law of thermodynamics which can be applied to the condenser. In the condenser, the high *temperature refrigerant* will lose its *heat* to the cooler air above. *Heat* will spontaneously flow from the high *temperature refrigerant* to the lower *temperature* atmosphere. As a result, the *temperature* of the *refrigerant* will decrease. The *temperature* of the *refrigerant* continues to decrease until the *refrigerant* begins to change phase. At that point, the *temperature* of the *refrigerant* remains constant. During phase change, latent *energy* is released as *heat* to the house.

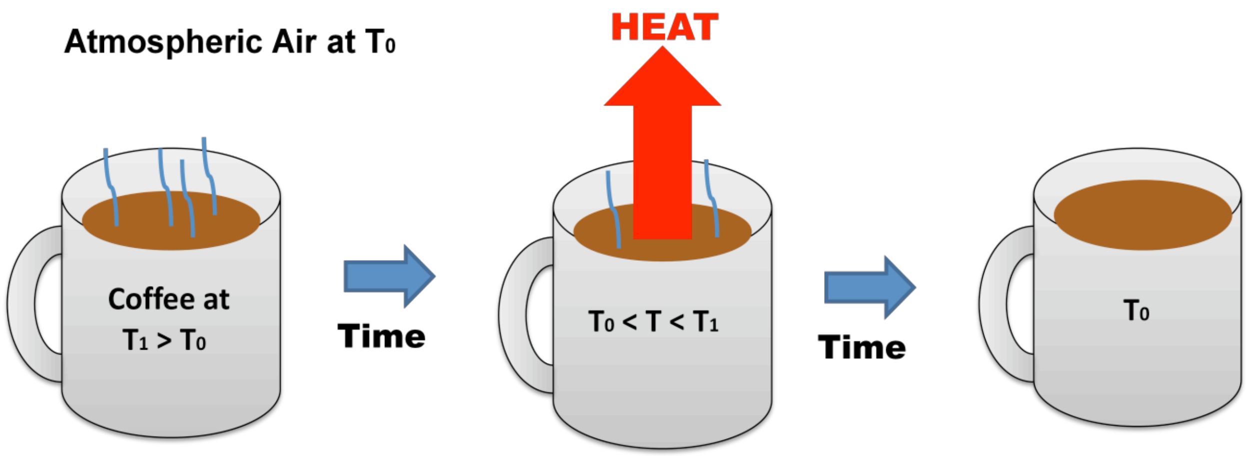


Figure 11 –A cup of hot coffee at temperature (T_1) greater than the temperature of the atmosphere (T_0) [Sahil Kazi]

3.3.4 How Is Energy Conserved During Condensation? (Conservation of Energy)

During the condensation process, *energy* is conserved. The *law* of conservation of *energy* (refer to section 3.2.2.2) enables us to understand how *energy* is conserved. This *law* states that *energy* can neither be created nor destroyed [13]. As a result, *energy* can only be transformed from one state to another [13]. In the condenser, the release of latent *energy* during phase change transforms into *heat,* also a form of *energy.* Thus, *energy* is conserved. This *heat* then rises and warms the cooler air above the condenser. As a result, the *temperature* of the air rises.

3.3.5 Summarizing the Condenser

The condenser completes the *heat* transfer process. *Energy* absorbed by the *refrigerant* from the ground (the evaporator) is pumped by a compressor into the condenser. As a result of the difference in *temperature* between the *refrigerant* in the coils and the air above, phase change is initiated causing the release of latent *heat.* The release of latent *heat* causes the *temperature* of the cooler air inside the house to increase. This is a result of the second law of thermodynamics. Throughout each process, the total *energy* remains constant, thus *energy* was conserved (law of conservation of energy). The final process, completing the *heat* pump cycle of the GSHP, is the expansion process by an expansion valve (see section 3.4.).

3.4 Expansion Valve

In this section, we will explain the operation of the expansion valve and describe a simplified expansion process.

The expansion (or throttle) valve (see Fig. 12 below) is the fourth and final major component in the GSHP's heating cycle. The valve is usually located in the same place as the compressor (see Fig. 5 above in section 3.2), about halfway between the evaporator and the condenser (see Fig. 2 in section 2.1)

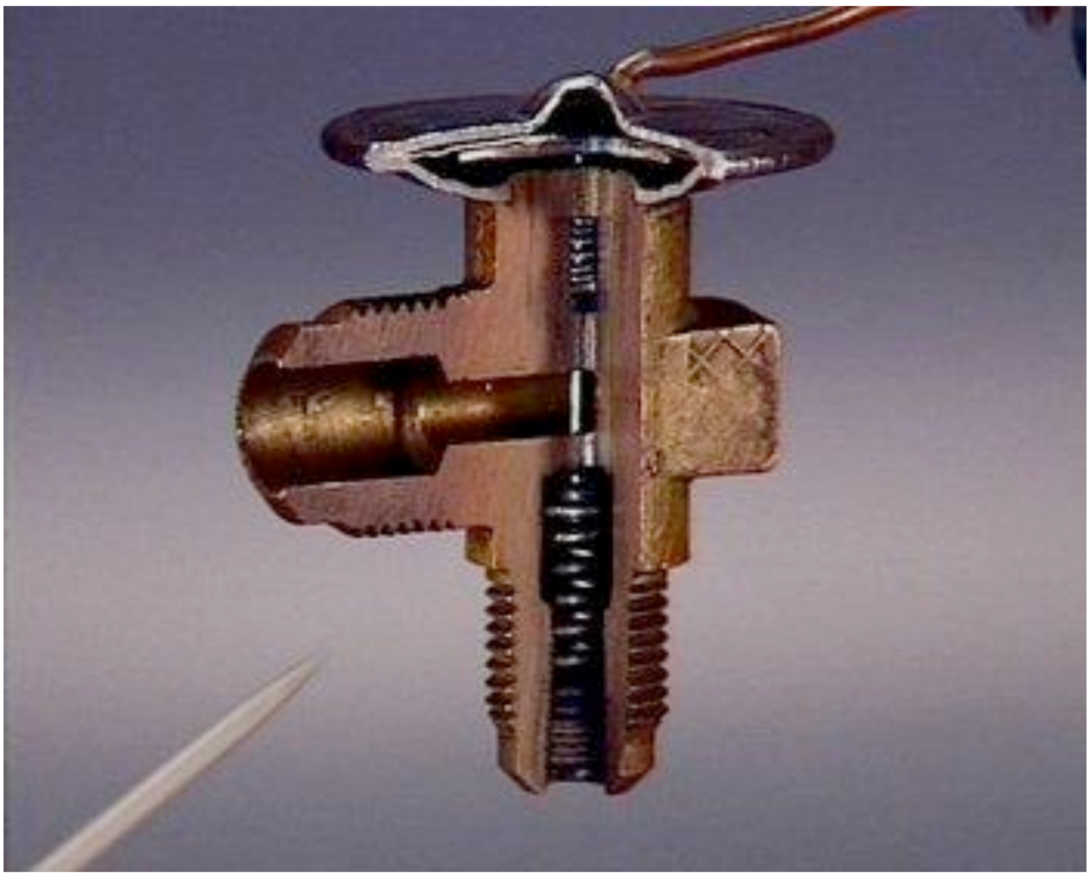


Figure 12. A typical expansion valve [31]

It is the counterpart to the compressor [32] which the high pressure *liquid refrigerant* must pass through in order to reach the evaporator after leaving the condenser. The primary purpose of the expansion valve is to sufficiently decompress the *refrigerant* to allow it to boil in the evaporator. This can be done simply by increasing the diameter of the pipe in which the *refrigerant* is flowing as shown in Fig. 13 below.

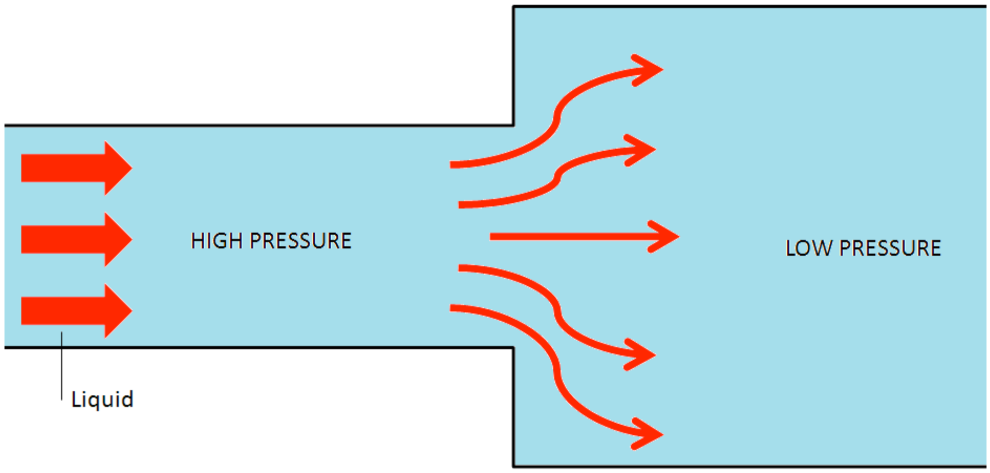


Figure 13. The expansion process [Christophe SIEWECKE]

As mentioned in section 3.2.2.2, volume and pressure are inversely proportional. What this means for the fluid passing through the expansion valve is that once the diameter of the pipe increases, the volume will also increase, causing the pressure to drop. The expansion process will also result in a significant *temperature* drop [3], which, with low pressure, will allow the *refrigerant* to boil once again in the evaporator and restart the *heat*ing cycle.

4.0 Conclusion

In closing, we hope that this document contributes to an understanding of how a GSHP works.

We are available to answer any questions and respond to any concerns that may arise. We are also open to make changes where necessary to better integrate this document with the KEN website. Please contact us by email at: group8gshp@groups.live.com

Glossary of Terms

CFCs and HCFCs: Refrigerants which have been banned because of their serious damage to the ozone layer when released into the atmosphere [9].

Chemical Properties: Properties which describe how a substance changes into a completely different substance [33].

Direct expansion GSHP: A GSHP in which the refrigerant flows directly into the compressor once it leaves the evaporator [28].

Electromagnetic waves: Another term for light. Light waves are fluctuations of electric and magnetic fields in space [34].

Energy: Equivalent, but not limited, to the ability to exert a push or pull on another object. Energy can take on many forms [35].

Gas/Gaseous: One of the three physical states of matter. A gas fills its container, taking both the shape and the volume of the container [26].

Greenhouse gases: Group of gases, including carbon dioxide (CO2), which contributes to the greenhouse effect. This effect is thought to be the cause of Global Warming [36].

Heat/Heat energy: Heat energy is the result of the movement of atoms, molecules or ions in solids, liquids and gases. Heat energy can be transferred from one object to another and the transfer or flow due to the difference in temperature between the two objects is called heat [37].

Liquid: One the three physical states of matter. Occupies a fixed volume (shape of container) [33].

Mechanical energy: Mechanical energy is the energy that is possessed by an object due to its motion or due to its position [38].

Molecules: A group of two or more atoms held together by bonds [39].

Normal Boiling Point: Temperature at which a substance boils at atmospheric pressure [40].

Nuclear fusion: Process by which nuclear reactions between light elements form heavier elements [41].

Ozone layer: Layer of ozone (O_3) that is in the upper atmosphere. It protects Earth from ultraviolet (UV) radiation which causes sunburns [42].

Physical Properties: Properties which can be observed without changing the identity of a substance [33].

Piston: A solid cylinder or disk that fits into a hollow cylinder and moves back and forth under the pressure of a fluid, or moves or compresses a fluid, as in a pump or compressor [43].

Refrigerant: Substance such as R-134a used in heat pump/refrigeration cycles (such as a refrigerator) to transfer heat [44].

Solar system: The solar system is the sun, its eight major planets, the dwarf planets and small bodies, and interplanetary dust and gas under the sun's gravitational control [45].

Solid: One of the three states of matter. Solids hold their shape and have a fixed volume [26].

Temperature: Measure of the kinetic energy of molecules (measure of how fast molecules are moving) [46].

Thermal Conductivity: The measure of the ability of a material to transfer heat. The higher the thermal conductivity, the more easily heat will be transferred by the material [47].

References

[1] "About KEN," http://www.kanataenvironmentalnetwork.com/about, Accessed May 25, 2011.

[2]A. Leech. "Why are ground source heat pumps being left behind?" http://www.4ecotips.com/eco/4ecoimages/How%20does%20a%20GSHP%20work.jpg, Accessed May 15, 2011.

[3] Natural Resources Canada, "Ground-Source Heat Pump Analysis Chapter," RETScreen International, 2001-2005. Available online at: www.retscreen.net/download.php/ang/479/0/Textbook_GSHP.pdf, Accessed June 11, 2011.

[4] Encyclopedia Britannica, "Solar System," http://www.britannica.com/EBchecked/topic/553008/solar-system, Accessed June 18, 2011.

[5] Encyclopaedia Britannica, "Radiation," http://www.britannica.com/EBchecked/topic/488507/radiation, Accessed June 18, 2011

[6] "Energy Rules," http://www.uwsp.edu/cnr/wcee/keep/Mod1/Rules/EnTransfer.htm , Accessed June 18, 2011.

[7] Soil temperature, "factors affecting soil temperature," http://lawr.ucdavis.edu/classes/ssc107/SSC107Syllabus/chapter8-01.pdf , Accessed June 28, 2011.

[8] R. H. D. Rawlings and J. R. Sykulski, "Ground source heat pumps: A technology review," *Building Services Engineering Research & Technology*, vol. 20, no. 3, pp 119-129, January 1999.

[9] P. Le Feuvre, "An Investigation into Ground Source Heat Pump Technology, its UK Market and Best Practice in System Design," M. Sc. Thesis, University of Strathclyde, UK, 2007.

[10] S. Gopalnarayanan, "Choosing the right refrigerant," http://www.memagazine.org/backissues/membersonly/october98/features/refrig/refrig.html, Oct. 1998, Accessed June 11, 2011.

[11] W. E. Glassley, "Low Temperature Geothermal Resources: Ground Source Heat Pumps" in *Geothermal Energy: Renewable Energy and the Environment*, Abbas Ghassem, Ed. Boca Raton, FL: CRC Press, 2010, ch. 10, pp. 183-199.

[12] P. Fishbane, S. Gasiorowicz, S. Thornton, *Physics for Scientists and Engineers*, vol. 1, 3rd ed. Pearson Prentice Hall: Pearson Education Inc., 2005

[13] "Phases of Matter," http://www.grc.nasa.gov/WWW/K-12/airplane/state.html, Accessed June 12, 2011.

[14] "Heat," www.explainthatstuff.com/heat.html, Accessed: June 12, 2011

[15] *"Energy in Thermal Process",* http://astro1.panet.utoledo.edu/~gthomps/Chapter11.pdf Accessed June 18, 2011.

[16] "Gas Compressor Definition," www.waterfuelconverters.com/GasCompressor.html, Accessed June 10, 2011.

[17] "Eco Solar Potential," http://ecosolarpotential.co.uk/html/misc/gallery.html, Accessed June 12, 2011.

[18] "Principles of Hydraulics," http://www.edgeroamer.com/sweethaven/mechanics/hydraulics01/default.asp?iNum=0301, Accessed June 10, 2011.

[19] M. J. Moran and H. N. Shapiro, "Control Volume Analysis Using Energy" in *Fundamentals of Engineering Thermodynamics*, 6th ed., New Jersey: John Wiley & Sons, 2008, pp. 167.

[20]"Types of Compressors," http://www.refrigers.com/content/view/31517/28/, Accessed June 10, 2011.

[21] R. Nave, "Pressure," http://hyperphysics.phy-astr.gsu.edu/hbase/press.html, Accessed June 10, 2011.

[22] "Ideal Gas Law," http://hyperphysics.phy-astr.gsu.edu/hbase/kinetic/idegas.html, Accessed June 10, 2011.

[23] "The Law of Conservation of Energy," http://library.thinkquest.org/2745/data/lawce1.htm, Accessed June 10, 2011.

[24] S. Kavanaugh, "How ground/water source heat pumps work," http://www.geokiss.com/consumer-info/HowG&WSourceHeatPumpsWork.pdf Accessed June 18, Accessed June 20, 2011.

[25] "Underfloor heating," http://allstarplumbing.co.uk/?page_id=53, Accessed June 12, 2011.

[26] "Phases of Matter," http://www.grc.nasa.gov/WWW/K-12/airplane/state.html, Accessed June 12, 2011.

[27] "Heat," www.explainthatstuff.com/heat.html, Accessed June 12, 2011.

[28] "Boiling point," http://hyperphysics.phy-astr.gsu.edu/hbase/kinetic/vappre.html, Accessed June 1st, 2011.

[29] J. Haby, "Understanding Latent Heat," http://www.theweatherprediction.com/habyhints/19/ Accessed June 12, 2011.

[30] K. A. Lemke, "Earths Radiation and Energy Balance," http://www.uwsp.edu/geo/faculty/lemke/geog101/lectures/02_radiation_energy_balance.html, Accessed June 12, 2011.

[31] "Thermostatic expansion valve system," http://www.cdxetextbook.com/hvac/heatAir/thermalExpan/TXvalve.html, Accessed June 11, 2011.

[32] "Investigating the function of the expansion valve of the heat pump," http://www.ld-didactic.de/literatur/hb/e/p2/p2632_e.pdf, Accessed June 11, 2011.

[33] "Physical and Chemical Properties," http://www.ndt-ed.org/EducationResources/CommunityCollege/Materials/Physical_Chemical/PhysicalProperties.htm, Accessed June 15, 2011.

[34] "Electromagnetic Wave", http://space.about.com/od/glossaries/g/electromagwave.htm, Accessed June 18, 2011.

[35] R. Nave, "Energy," http://hyperphysics.phy-astr.gsu.edu/hbase/enecon.html, Accessed June 15, 2011.

[36] "Greenhouse Gas Emissions," http://www.epa.gov/climatechange/emissions/index.html, Accessed June 20, 2011.

[37] "Heat Energy," http://www.sciencelearn.org.nz/Contexts/Fire/Science-Ideas-and-Concepts/Heat-energy, Accessed June 15, 2011.

[38] "Mechanical Energy," http://www.physicsclassroom.com/class/energy/u5l1d.cfm Accessed June 15, 2011.

[39] "Molecules," http://www.historyoftheuniverse.com/molecule.html, Accessed June 15, 2011.

[40] "Boiling," http://www.chem.purdue.edu/gchelp/liquids/boil.html, Accessed June 20, 2011.

[41] Encyclopedia Britannica, "Nuclear Fusion" http://www.britannica.com/EBchecked/topic/421667/nuclear-, Accessed June 18, 2011

[42] "The Ozone Layer," http://www.nas.nasa.gov/About/Education/Ozone/ozonelayer.html, Accessed June 20, 2011.

[43] Dictionary.com, "Piston," in *The American Heritage Science Dictionary*, Houghton Mifflin Company, http://dictionary.reference.com/browse/piston, Accessed June 15, 2011.

[44] "Refrigerants," http://www.des.state.nh.us/organization/commissioner/pip/factsheets/ard/documents/ard-37.pdf, Accessed June 20, 2011

[45] Encyclopedia Britannica, "Solar System" http://www.britannica.com/EBchecked/topic/553008/solar-system, Accessed June 18, 2011

[46] "Temperature and Kinetic Energy," http://eo.ucar.edu/webweather/molecules.html, Accessed June 15, 2011.

[47] "Thermal Conductivity," http://www.ndt-ed.org/EducationResources/CommunityCollege/Materials/Physical_Chemical/ThermalConductivity.htm, Accessed June 20, 2011