CHAPTER
TWO

Basic Concepts

Chapter 2 focuses on the basic physical concepts concerning natural convection heat exchangers. This chapter covers the basics of natural convection; the relationships between tank stratification, low collector flow rates, and system performance; and the distinction between natural and forced convection in the natural convection heat exchanger. The solar fraction is defined, the tank energy balance is outlined, and the shell and coil heat exchanger geometry is briefly presented.

2.1 Natural Convection in Fluid Loops

Consider the system in Figure 2.1.1. When solar radiation is above a level needed to overcome thermal losses, glycol will be pumped through the collector where it is heated and then into the NCHE. Energy will be transferred from the hot glycol to the cold water in the heat exchanger. The water in the heat exchanger becomes hot, while the water in the tank remains cool. As cool water is denser than hot water, the water in the tank will be denser than the water in the heat exchanger. Consequently the tank water will be heavier. The tendency will be for the heavier water to seek the lowest point. In order to do so, it must push the lighter, hotter water in the NCHE away, through point 1, into the tank. As the cooler water enters the heat exchanger from the tank, it in turn will be heated, become less dense, and be pushed away by still more water from the tank.

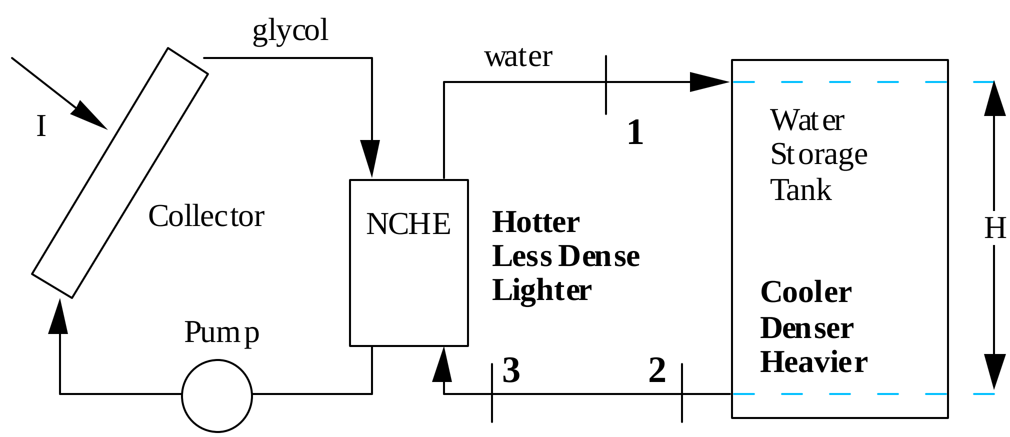

Figure 2.1.1 Diagram of Solar Domestic Hot Water System.

Consider the pressure at point 1 in Figure 2.1.1 to be at some nominal value. Assume the pressure experienced at points 2 and 3 is due only to the static pressure of the water in the tank and NCHE respectively. This would be the case when there is no flow. The following equations are used to calculate the pressures at points 2 and 3:

$$P_2 = P_1 + \overline{\rho}_{tk} g H \quad (2.1.1)$$

$$P_3 = P_1 + \overline{\rho}_{HX} g H \quad (2.1.2)$$

where g = gravitational constant
$\overline{r}_{tk} = average$ tank density
$\overline{r}_{HX} = average$ HX density
H = horizontal distance from 1 to 2

As the temperature is greater in the heat exchanger than in the tank, the water will be less dense in the heat exchanger, and therefore P_3 will be smaller than P_2. As flow originates from higher pressures and flows toward lower pressures, flow will commence, proceeding from point 2 to point 3.

Once the fluid is flowing, the shear pressure drop in the pipes and heat exchanger needs to be considered. High shear pressure drops in a piping system slow the water flow rate. Thin diameter pipes, long pipes, and too many fittings and valves make up systems with overly large shear pressure drops. Differences in static pressure contribute to flow rate. The presence of large shear pressure drops hinders the flow.

2.2 The Shell and Coil Heat Exchanger

Thermo Dynamics Ltd. of Nova Scotia manufactures a shell and coil, sidearm NCHE. The heat exchanger comprises four helices of copper tubing with a combined length of 100 feet wound around a core in a four inch diameter cylindrical shell. Top and side views of the sidearm heat exchanger are shown in Figures 2.2.1,2. The glycol flows within the helical copper tubes, the water flows outside the tubes. More detailed descriptions can be found in Appendix A.

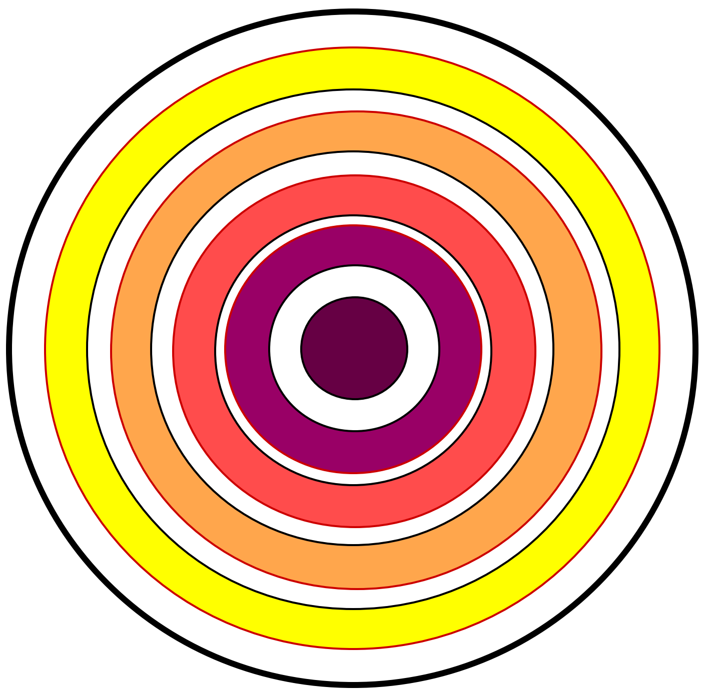

Figure 2.2.1 Top cutaway view of Thermo Dynamics' shell and coil heat exchanger.

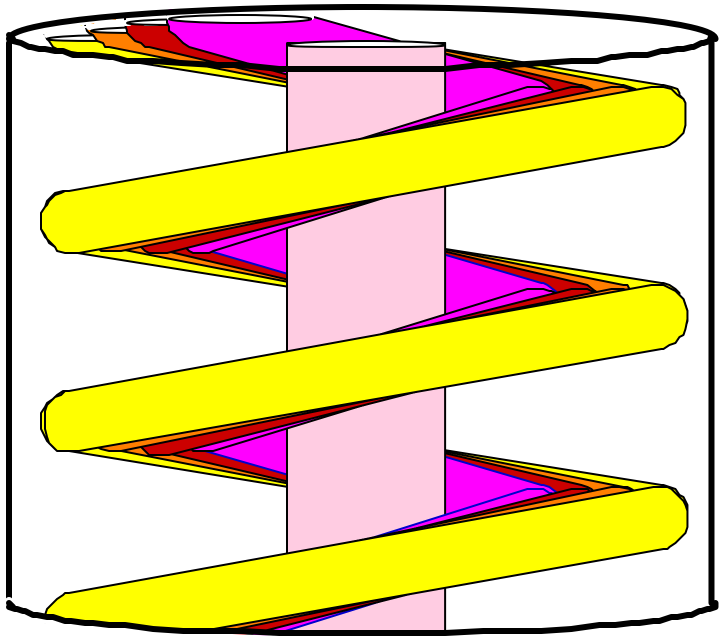

Figure 2.2.2 Side view of Thermo Dynamics' shell and coil sidearm heat exchanger.

2.3 Natural Convection and Forced Convection

Although natural convection drives the water flow, at higher flow rates the flow *experienced in* the NCHE is forced. It is necessary to distinguish between natural convection in the water loop and natural convection within the heat exchanger itself as these have different heat transfer characteristics. *Natural convection in the water loop* is, as described above, due to density differences around the water loop. In the heat exchanger, this type of natural convection is experienced as a forced flow, and the heat transfer in the heat exchanger is due to primarily forced convection. In contrast, *Natural convection within the heat exchanger* is due to local density gradients within the heat exchanger. At low flow rates these natural convection effects become evident. Although the water is being propelled by forced convection, some of the water in the heat exchanger is moving on its own due to localized natural convection. When the copper tubes are hot, the water that comes close to the tubes will be heated, become less dense, and displace the nearby water that does not come into contact with the copper tubes. In this case flow can be characterized as a combination of forced and natural convection.

Although natural convection in the heat exchanger enhances heat transfer at low water flow rates, in this work its effects are neglected. Fraser wrote a density correction factor to account for natural convection in the heat exchanger, but this factor had little effect on simulation results. This topic is covered in detail in Sections 3.5.1 and 4.3.1.

2.4 Tank Stratification and System Efficiency

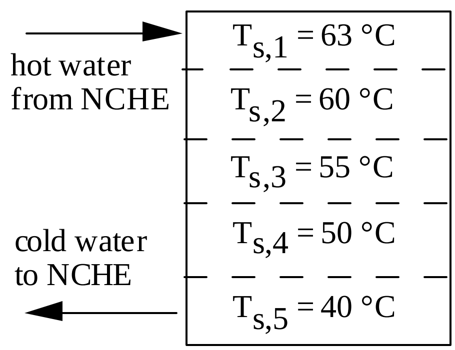

Figure 2.4.1 Five node stratified water storage tank.

Water storage tanks have a tendency to stratify. Due to natural convection effects within the tank, hot water rises to the top of the tank while cool water sinks to the bottom. From simulation studies done on tank stratification, performance of SDHW systems with stratified tanks perform one-third better than systems with fully mixed tanks (Wuestling et al. 1985). Lower water temperatures at the tank's bottom node entering the heat exchanger increase the heat transfer in the heat exchanger. Hotter temperatures at the top tank nodes contribute to reduced need for auxiliary heating. This degree of improvement of stratified tanks over mixed tanks is not fully realized in practice as real tanks are neither fully mixed or stratified, and water draws tend to mix the tank, destroying stratification. Ultimately, load patterns and collector radiation input determine the level of system enhancement due to tank stratification (Duffie and Beckman 1991).

2.5 Low Collector Flow Rates and System Efficiency

The SDHW system analyzed in this work utilizes glycol flow rates much lower than for standard SDHW systems. Typically glycol flow rates range from 0.01 to 0.02 kg/m^2-s. Low flow systems, such as the system under study, generally have glycol flow rates in the range of 0.002 to 0.007 kg/m^2-s. Low flow systems are associated with lower collector efficiencies. In low flow systems, the glycol heats up more in the collector, and when hot takes in a reduced amount of thermal energy. In the heat exchanger, low glycol flow rates reduce heat transfer. As less energy is transferred to the water in the NCHE, water flow rates become lower. Low water flow rates into the tank better preserve tank stratification, which in turn increases system efficiency.

On the one hand higher glycol flow rates account for greater collector and heat exchanger performance, yet on the other hand lower glycol flow rates lead to greater tank performance. Every system has an optimal glycol flow rate wherein the benefits and detriments just described are balanced, and where the system performs best. One of the goals of this study will be to find the best configuration of system parameters, including glycol flow rate, which leads to optimal system performance.

2.6 The Solar Fraction

For households employing SDHW systems, domestic water heating needs are met by a combination of solar and conventional (auxiliary) energy sources. Solar energy usually meets a fraction of the total heating load, while auxiliary energy is used to provide the balance of the water heating requirement, that is:

$$Q_{req} = Q_{solar} + Q_{aux} \qquad (2.6.1)$$

where Q_{req}, Q_{solar} and Q_{aux} are respectively the required load, the portion of required load met by solar water heating, and the portion of the load met by conventional water heating methods (auxiliary heating).

The solar fraction is defined as the fraction of the annual water heating load supplied by solar energy (Duffie and Beckman 1991), which is given by:

$$SF = \frac{Q_{req} - Q_{aux}}{Q_{req}} \qquad (2.6.2)$$

The solar fraction is used for determining relative SDHW system performance. In this work, simulations are run in order to generate solar fractions, which are then compared in order to determine the best SDHW system.

2.7 Water Storage Tank Energy Balance

An energy balance is presented for a water storage tank:

$$\dot{Q}_{in} = \dot{Q}_{load} + \dot{Q}_{env} + DU_{tank} \tag{2.7.1}$$

where $\dot{Q}_{in}$, $\dot{Q}_{load}$, $\dot{Q}_{env}$, and DU_{tank} are respectively the rate of energy addition from the NCHE, the rate of energy removal to the load, the rate of energy loss to the tank's surroundings, and the change in internal energy of the tank.

The accuracy of a TRNSYS simulation is represented by the energy balances on the water storage tank. The energy flowing into the tank should equal the combination of the energy flowing out of the tank and the change in internal energy of the tank. A tank energy balance percent difference is calculated for the simulations using:

$$Energy\ Balance\ \ Percent\ \ Difference = \frac{\left(\dot{Q}_{in} - \left(\dot{Q}_{load} + \dot{Q}_{env} + DU_{tank}\right)\right)}{\frac{\left(\dot{Q}_{in} + \left(\dot{Q}_{load} + \dot{Q}_{env} + DU_{tank}\right)\right)}{2}} \times 100 \tag{2.7.2}$$

Energy balances percent differences were below 1.1 % for all simulations.