# ABSTRACT

The use of simulations can greatly aid in optimizing the design of natural convection heat exchangers (NCHEs) in solar domestic hot water (SDHW) systems. Fraser et al. (1992) presented a NCHE model that is used in the WATSUN solar simulation program, that requires experimental measurements of the heat exchanger thermal performance and shear pressure losses. Two TRNSYS models are here presented for a NCHE in a SDHW loop. The simple model, based on Fraser et al.'s work, requires experimental testing on the particular heat exchanger. The simple model can be used for optimizing SDHW system parameters (i.e. pipe lengths and diameters, collector areas, tank volume etc.) excluding the NCHE itself which is represented by the experimental curves. A detailed model, based upon cross flow correlations, requires geometric specifications of the NCHE being simulated and is applicable to shell and coil and counterflow configurations. By varying heat exchanger geometric parameters (such as the number of helices, diameters of helices, diameter and length of the heat exchanger shell) the detailed model can be used to design an optimum NCHE. Results comparing the detailed model with Fraser et al.'s experiments show reasonable agreement. Using the detailed model and the least cost savings economic analysis, simulations were performed to discover the optimal shell and coil NCHE geometry. It was found that considerably reducing the heat exchanger size led to enhanced economic performance over a 10 year period of economic analysis. Coil spacing and tube diameter had a lesser impact upon system performance than heat exchanger shell length and number of

helices. Thermo Dynamics Inc. manufactures a shell and coil NCHE that contains 4 coils and is 0.635 m. The optimal heat exchanger design contains 2 helices and is 0.45 m long. For a given set of system parameters, a SDHW system containing the optimally designed heat exchanger would save the consumer an extra $110 in initial equipment cost, and $52 over a 10 year period. Heat exchanger designs were subject to variations in system parameters, such as collector area, hot water draw, location and glycol flow rate. Although each set of system parameters suggested a different optimal design, overall, the optimal design found for the initial set of system parameters remained adequate. As different economic assumptions will lead to differing optimal heat exchanger lengths, this work can serve as a guide for those who desire to optimize a shell and coil NCHE based upon a prevailing set of economic assumptions.

# ACKNOWLEDGMENTS

Oftentimes in the midst of this research problem I felt like a man lost in a labyrinth of old. Wherein the object of my labor was to escape the labyrinth alive and in a timely fashion, I could never truly know which path would lead me safely out of the labyrinth. I could spend countless hours along one path only to find an insurmountable wall before me, or even worse a Minotaur with a club. Many times I encountered these dead ends and the deadly beast, and was nearly bludgeoned to death once or twice. Still I managed to escape the labyrinth of grad school research alive. This work details the path I used to escape the labyrinth, so that others when faced with the problems of modeling NCHEs, may quickly and safely resolve the problem, and move onto other challenges.

I would like to thank my advisors, Bill Beckman, and Sandy Klein for their guidance in this work. I would also like to thank my compatriots at the Solar Lab for the community we were able to establish. Thanks also to my wife, Karen, for her patience in the research process; Bill Wyatt for his sound advice on how to avoid injury or death at the hands of the Minotaur; Alexander (Raskolnikov) Fiksel for his help with TRNSYS; James Naismith for inventing the Game; Pushkin, Goethe, Renoir, Dr. Zhivago and Chagall for reminding me that there is life outside of grad school; and all the boys on the court for allowing me to hit, kick and pound on them at will.

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# NOMENCLATURE

| | |
|---|---|
| $a$ | fitting or curve radius [m] |
| $A$ | area [m$^2$] |
| $A_c$ | collector area [m$^2$] |
| BACK | using TRNSYS' backsolver |
| $C^*$ | ratio of glycol to water capacitance rates |
| $C_A$ | cost of solar equipment which is a function of collector area [\$/m$^2$] |
| $C_b$ | yaw angle pressure correction factor |
| $C_E$ | cost of solar equipment which is independent of collector area [\$] |
| $C_p$ | specific heat [J/kg-°C] |
| $D$ | diameter [m] |
| DCF | density correction factor |
| DHW | domestic hot water |
| $DU_{tank}$ | change in internal energy of water storage tank [J] |
| $De$ | Dean number |
| $F$ | flow number; solar fraction |
| $f_D$ | Darcy friction factor |
| $f_j$ | Jakob's friction factor |
| $g$ | gravitational acceleration [m/s$^2$] |
| $h$ | heat transfer coefficient [W/m$^2$-°C] |
| $H$ | height [m] |
| $k$ | conductivity [W/m-°C] |
| $K$ | minor loss coefficient |
| $K^*$ | minor loss coefficients found using Hooper's correlation |
| $K_1$ | minor loss coefficient at Re = 1 |

| | |
|---|---|
| $K_8$ | minor loss coefficient at Re = 8 |
| $L$ | length [m] |
| LCC | the sum of all costs associated with an energy delivery system over its lifetime or over a period of economic analysis [$] |
| *LCS* | the difference between the LCC of a conventional DHW system and the LCC of a solar plus auxiliary energy DHW system [$] |
| *DLCS* | the difference in *LCS* using two different energy delivery systems [$] |
| $\dot{m}$ | flow rate [kg/s] |
| $\dot{m}_{w,1}$ | 1st water flow rate entry in modified effectiveness data file [kg/s] |
| $N$ | total number of tubes in equivalent tube bundle |
| NBTS | non-backsolving time step |
| $N_L$ | number of tubes in flow direction in equivalent tube bundle |
| $N_T$ | number of tubes in transverse direction in equivalent tube bundle |
| *NTU* | number of transfer units |
| *Nu* | Nusselt number |
| $P$ | pressure [Pa] |
| *DP* | pressure difference, pressure loss, pressure gain [Pa] |
| $P_1$ | ratio of life cycle fuel costs to 1st year fuel costs |
| $P_2$ | ratio of life cycle expenditures that occur due to additional capital investment in the energy delivery system to the initial cost |
| *Pr* | Prandtl number |
| $Q$ | heat transfer rate [W] |
| *Ra* | Rayleigh number |
| *Ra** | modified Rayleigh number |
| $Re_D$ | Reynolds number |
| $Re_{D,max}$ | maximum Reynolds number found in equivalent tube bundle in cross flow |

| | |
|---|---|
| RFS1 | combination of regula falsi and TRNSYS' new solver |
| RFSS | combination of regula falsi and TRNSYS' successive substitution |
| $S'$ | dimensionless flow space |
| SDHW | solar domestic hot water |
| $SF$ | solar fraction |
| $S_{C,S}$ | distance from outer diameter of outermost coil to shell [m] |
| $S_L$ | coil spacing in flow direction [m] |
| $S_T$ | coil spacing in transverse direction [m] |
| $T$ | temperature [°C] |
| $T_s$ | coil average surface temperature [°C] |
| $T_{s,1}$ | tank storage node temperature [°C] |
| $DT$ | change in temperature [°C] |
| $UA_S$ | product of overall heat transfer coefficient and heat transfer area [W/°C] |
| $U$ | velocity [m/s] |
| $W$ | Fraser's density correction factor |
| $z$ | height of node [m] |
| $Z$ | depth of equivalent tube bundle [m] |

**Greek Symbols:**

| | |
|---|---|
| $b$ | yaw angle [°] |
| $e$ | effectiveness |
| $e'$ | modified effectiveness |
| $e'_1$ | 1st entry in modified effectiveness data file |
| $r$ | density [kg/m$^3$] |
| $m$ | absolute viscosity [Pa-s] |

| | |
|---|---|
| $n$ | kinematic viscosity [$m^2/s$] |

**Subscripts:**

| | |
|---|---|
| $c$ | coil |
| $cf$ | counterflow assumption in place; cross flow sectional |
| $D_{hx}$ | based upon hydraulic diameter |
| $e$ | effective |
| $eq$ | equivalent |
| $exp$ | experimental |
| $g$ | glycol |
| $g,i$ | glycol inlet |
| $g,o$ | glycol outlet |
| $HX$ | heat exchanger |
| $i$ | inside |
| $max$ | maximum |
| $min$ | minimum |
| $o$ | outside |
| $P$ | pipes |
| $s$ | storage; surface |
| $sh$ | shear |
| $s,i$ | inner surface |
| $s,o$ | outer surface |
| $st$ | static |
| $tk$ | tank |
| $t,o$ | tube outer |
| $w$ | water |

| | |
|---|---|
| $w,i$ | water inlet |
| $w,o$ | water outlet |