ACKNOWLEDGEMENT

I would like to dedicate this thesis to my wife, Soo Jeong Lee. Without you, I would have never accommodated myself into new environment and finished my graduate course in Madison. I love you. This is for you. Mom and Dad, you always have taken care of me even though I have been far away from you. You made me who I am. I always thank you and respect your thought and life.

I would like to thank my advisors, William A. Beckman and John W. Mitchell, for all of your concern and advice. It was an honor to work under the direction of you. I would also like to thank to Professor Sanford A. Klein. I have been impressed at your ability to look at a problem form an entirely different perspective. I wanted to learn your ability but I am not sure whether I did or not. All of you have always encouraged me to do my work with confidence.

Thanks to Solar Energy Laboratory. We had a seminar every week that gave me chances to meet various areas. Actually I could not understand every word due to my poor English. But it was really great to have a chance to present my work and listen to others.

Thanks to Joon Sik Park, my senior from Hong-Ik University. You gave me a lot of advice for my study and life in Madison. I really would like to have a chance to work with you in near future.

And finally, thanks to my brother and sister for your concern and encouragement.
Flat-plate solar collectors have potential applications in HVAC system, industrial thermal process, and solar engineering. Flat-plate collectors are the most economical and popular in solar domestic heating water system since they are permanently fixed in positions, have simple construction, and require little maintenance. The design of a solar energy system is generally concerned with obtaining maximum efficiency at minimum cost. The aim of this thesis is to develop a design tool for predicting the performance of a flat-plate solar collector.

A very detailed thermal analysis of a flat-plate solar collector was carried out to predict the thermal performance. The analysis is based on the established theory about flat-plate solar collector: the radiation absorption, heat loss from the collector, and temperature distribution on the plate. The calculation of useful energy and top heat loss from the collector is based on the aperture area to make a more accurate prediction of collector performance. The net-radiation method was employed to obtain the radiation component of top heat loss from the general collector cover system. The correlation for natural convection heat transfer between the covers and between the plate and cover was selected with the consideration of the low conductivity of plastics. The semi-gray radiation model was adopted to determine the optical properties of the collector cover and absorber plate.

Results comparing the design tool calculations with experiments showed good agreement. The collector tests were performed by Florida Solar Energy Center. The
calculations based on the information from test reports yielded an accurate prediction of the thermal performance of flat-plate solar collectors.

Based on the analysis, a flat-plate solar collector design program (CoDePro) has been developed. The program is arranged so that detailed information about the collector can be specified with an easy-to-use graphic interface. Compiled versions of CoDePro have been distributed to solar engineers from its development level, and it has been modified according to their suggestions. CoDePro has an ability to evaluate the collector performance with high accuracy and can be used as a design tool for flat-plate solar collectors.
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### NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_c$</td>
<td>Gross collector area</td>
</tr>
<tr>
<td>$A_e$</td>
<td>Edge area of collector</td>
</tr>
<tr>
<td>$A_p$</td>
<td>Aperture area</td>
</tr>
<tr>
<td>$b_0$</td>
<td>Incidence angle modifier coefficient</td>
</tr>
<tr>
<td>$C_b$</td>
<td>Tube-plate bond conductance</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Specific heat of working fluid</td>
</tr>
<tr>
<td>$D$</td>
<td>Outer diameter of tube</td>
</tr>
<tr>
<td>$D_i$</td>
<td>Inner diameter of tube</td>
</tr>
<tr>
<td>$F$</td>
<td>Fin efficiency of straight insulated-fins with rectangular cross section</td>
</tr>
<tr>
<td>$f$</td>
<td>Darcy friction factor</td>
</tr>
<tr>
<td>$F_R$</td>
<td>Collector heat removal factor</td>
</tr>
<tr>
<td>$F'$</td>
<td>Collector efficiency factor</td>
</tr>
<tr>
<td>$F''$</td>
<td>Collector flow factor</td>
</tr>
<tr>
<td>$G_T$</td>
<td>Total intensity of incident solar radiation on tilted collector surface.</td>
</tr>
<tr>
<td>$h_{fi}$</td>
<td>Forced convection heat transfer coefficient inside of tubes</td>
</tr>
<tr>
<td>$h_w$</td>
<td>Wind convection coefficient</td>
</tr>
<tr>
<td>$I$</td>
<td>Intensity of incident radiation</td>
</tr>
<tr>
<td>$K$</td>
<td>Minor loss coefficient</td>
</tr>
<tr>
<td>$K_{ta}$</td>
<td>Incidence angle modifier</td>
</tr>
<tr>
<td>$k$</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>$k_b$</td>
<td>Thermal conductivity of back insulation</td>
</tr>
<tr>
<td>$k_e$</td>
<td>Thermal conductivity of edge insulation</td>
</tr>
<tr>
<td>$L$</td>
<td>Characteristic length</td>
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<tr>
<td>$L_b$</td>
<td>Thickness of back insulation</td>
</tr>
<tr>
<td>$L_e$</td>
<td>Thickness of edge insulation</td>
</tr>
<tr>
<td>$L_{eq}$</td>
<td>Equivalent length</td>
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<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
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<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$m$</td>
<td>Parameter of the fin-air arrangement</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>Total collector mass flow rate</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of tubes</td>
</tr>
<tr>
<td>$n_1$</td>
<td>Refractive index of medium 1</td>
</tr>
<tr>
<td>$n_2$</td>
<td>Refractive index of medium 2</td>
</tr>
<tr>
<td>Nu</td>
<td>Nusselt number</td>
</tr>
<tr>
<td>$P$</td>
<td>Pressure</td>
</tr>
<tr>
<td>Pr</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>$Q$</td>
<td>Heat transfer rate</td>
</tr>
<tr>
<td>$q$</td>
<td>Radiation flux</td>
</tr>
<tr>
<td>$Q_c$</td>
<td>Heat transfer rate due to convection</td>
</tr>
<tr>
<td>$Q_r$</td>
<td>Heat transfer rate due to radiation</td>
</tr>
<tr>
<td>$Q_b$</td>
<td>Back heat loss from collector</td>
</tr>
<tr>
<td>$Q_e$</td>
<td>Edge heat loss from collector</td>
</tr>
<tr>
<td>$Q_u$</td>
<td>Useful gain from collector</td>
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<td>$Q_{\text{loss}}$</td>
<td>Overall heat loss from collector</td>
</tr>
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<td>$Q_t$</td>
<td>Top heat loss from collector</td>
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<tr>
<td>$r$</td>
<td>Reflection of radiation</td>
</tr>
<tr>
<td>$R_b$</td>
<td>Geometric factor</td>
</tr>
<tr>
<td>Ra</td>
<td>Rayleigh number</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>$S$</td>
<td>Absorbed radiation per unit area of absorber plate</td>
</tr>
<tr>
<td>$S_c$</td>
<td>Absorbed radiation per unit area based on the gross collector area</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
</tr>
<tr>
<td>$t$</td>
<td>Hour from midnight</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Ambient temperature</td>
</tr>
<tr>
<td>$T_b$</td>
<td>Fin base temperature</td>
</tr>
<tr>
<td>$T_f$</td>
<td>Local fluid temperature</td>
</tr>
<tr>
<td>$T_{fm}$</td>
<td>Mean fluid temperature</td>
</tr>
</tbody>
</table>
\( T_{dp} \)  Dew point temperature
\( T_i \)  Fluid temperature at collector inlet
\( T_o \)  Fluid temperature at collector exit
\( T_{pm} \)  Mean plate temperature
\( T_s \)  Sky temperature
\( U \)  Mean fluid velocity inside of tubes
\( U_L \)  Overall loss coefficient of the collector based on the gross collector area
\( U'_{L} \)  Overall loss coefficient of the collector based on the aperture area
\( V \)  Wind speed
\( W \)  Distance between the centers of adjacent tubes

**GREEK**

\( \alpha \)  Absorptance
\( \beta \)  Collector slope
\( \beta_v \)  Volumetric coefficient of expansion of air
\( \Delta \)  Difference
\( \delta \)  Thickness of absorber plate
\( \varepsilon \)  Emittance
\( \eta \)  Instantaneous efficiency of solar collector
\( \nu \)  Kinematic viscosity
\( \theta \)  Angle of incidence of solar radiation
\( \theta_1 \)  Angle of incidence
\( \theta_2 \)  Angle of refraction
\( \theta_{d,e} \)  equivalent angle of incidence for diffuse radiation
\( \theta_{g,e} \)  equivalent angle of incidence for ground-reflected radiation
\( \rho \)  Reflectance
\( \rho_f \)  
Density of working fluid

\( \sigma \)  
Stefan-Boltzmann constant

\( \tau \)  
Transmittance

\( \tau_a \)  
Transmittance of material due to absorption of radiation

\( \tau\alpha \)  
Transmittance-absorptance product

**Subscript**

\( b \)  
Beam radiation

\( c \)  
Cover

\( c1 \)  
Cover 1 (inner cover)

\( c2 \)  
Cover 2 (outer cover)

\( d \)  
Diffuse radiation

\( g \)  
Ground-reflected radiation

\( i \)  
Incidence radiation

\( n \)  
Normal incidence

\( p \)  
Absorber plate

\( r \)  
Reflected radiation

\( \perp \)  
Perpendicular component of radiation

\( \parallel \)  
Parallel component of radiation