# SIMULATION TECHNOLOGIES FOR NATURAL REFRIGERANT USE SYSTEM

Kiyoshi SAITO

Prof. of department of applied mechanics and aero space engineering
Director of institute for high production systems
WASEDA UNIVERSITY

# SIMULATOR DEVELOPMENT

In my institute, we develop simulators for **air-conditioning, refrigeration** systems that uses **natural refrigerant,** and **renewable energy** systems.

This simulator can calculate detailed performance and characteristics of these systems through the year for each countries' driving conditions that are essentials to **cost estimation, optimum design and optimum driving**.

But if you try to calculate these by yourself, you need very complex **mathematical techniques** →Next page.

Therefore, it is very difficult to carry out some calculations, even though you are **higher level researchers or engineers**.

This simulator is very **easy to handle** with help of Graphics. No need of mathematical back ground.

This simulator can be **opened through internet**. All the people in the world can access this simulator.

# EXAMPLES OF MATHEMATICS

## HEAT PUMP SYSTEMS

$$\frac{\mathrm{d}}{\mathrm{d}z_r}(\rho_r u_r)=0 \qquad \frac{\mathrm{d}}{\mathrm{d}z_r}\left(\rho_r u_r \frac{\pi d_{i,i}^{\ 2}}{4} h_r\right)=-q_i \qquad \frac{\mathrm{d}P_r}{\mathrm{d}z_r}=-f_{r,H}\frac{1}{d_{i,i}}\frac{\rho_r u_r^{\ 2}}{2}$$

$$\frac{\mathrm{d}}{\mathrm{d}z_w}(\rho_w u_w)=0 \qquad \frac{\mathrm{d}}{\mathrm{d}z_w}\left[\rho_w u_w\left(\frac{\pi d_{o,i}^{\ 2}}{4}-\frac{\pi d_{i,o}^{\ 2}}{4}\right)h_w\right]=q_i \qquad \frac{\mathrm{d}P_w}{\mathrm{d}z_w}=-f_{w,H}\frac{1}{d_{hyd}}\frac{\rho_w u_w^{\ 2}}{2}$$

$$q_i=K_i\pi d_{i,i}(T_r-T_w) \qquad \frac{1}{K_i\pi d_{i,i}}=\frac{1}{\xi_{gc}\cdot\alpha_i\pi d_{i,i}}+\frac{1}{2\pi\lambda_t}\ln\left(\frac{d_{i,o}}{d_{i,i}}\right)+\frac{1}{\alpha_o\pi d_{i,o}}$$

$$\mathrm{Nu}_r=\frac{(f_{r,H}/8)(\mathrm{Re}_b-1000)\mathrm{Pr}}{1.07+12.7\sqrt{f_{r,H}/8}\left(\mathrm{Pr}^{2/3}-1\right)} \qquad f_{r,S}=\left[1.82\log\left(\mathrm{Re}_f\right)-1.64\right]^{-2} \qquad f_{r,H}=f_{r,S}\left\{\mathrm{Re}_f\left(\frac{d_{i,i}}{D_H}\right)^2\right\}^{0.05}$$

$$\mathrm{Nu}_w=\left\{0.65\mathrm{Re}_w^{1/2}\left(\frac{d_{hyd}}{D_H}\right)^{1/4}+0.76\right\}\mathrm{Pr}_w^{0.175} \qquad f_{w,H}=f_{w,S}\left\{\mathrm{Re}_w\left(\frac{d_{o,i}}{D_H}\right)^2\right\}^{0.05} \qquad f_{w,S}=\frac{64}{\mathrm{Re}_w}$$

**Flow Pattern**

**Stratified-wavy flow, Annular flow, Intermittent flow and Bubbly flow**

$$\alpha_i=\frac{\theta_{dry}\alpha_{vapor}+(2\pi-\theta_{dry})\alpha_{wet}}{2\pi}$$

※$\theta_{dry}=0$ For Annular flow, Intermittent flow and Bubbly flow

Vapor phase heat transfer coefficient

$$\alpha_{vapor}=0.023\frac{\lambda_v}{D_{eq}}\mathrm{Re}_v^{0.8}\mathrm{Pr}_v^{0.4}$$

Wet wall boiling heat transfer coefficient

$$\alpha_{wet}=\left\{(S\alpha_{nb})^3+\alpha_{cb}^{\ 3}\right\}^{1/3}$$

Nucleate boiling heat transfer coefficient

$$\alpha_{nb}=131p_r^{-0.0063}(-\log_{10}p_r)^{-0.55}M^{-0.5}q^{0.58}$$

Convective boiling heat transfer coefficient

$$\alpha_{cb}=0.0133\frac{\lambda_l}{\delta}\mathrm{Re}_\delta^{0.69}\mathrm{Pr}_l^{0.4}$$

**Dryout region**

$$\alpha_{dryout}=\alpha_i(x_{di})-\frac{x-x_{di}}{x_{de}-x_{di}}\{\alpha_i(x_{di})-\alpha_{mist}(x_{de})\}$$

**Mist flow**

$$\alpha_{mist}=0.0117\frac{\lambda_v}{D_{eq}}\mathrm{Re}_H^{0.79}\mathrm{Pr}_v^{1.06}Y^{-1.83}$$

## DEHUMIDIFICATION SYSTEMS

$$\varepsilon\frac{\partial}{\partial t}(\rho_a w_a)+\nabla\cdot\mathbf{j}_p=\dot{m} \quad \text{pore}$$

$$\mathbf{j}_p=-\frac{\varepsilon D_p}{\tau_p}\nabla(\rho_a w_a)$$

$$\frac{1}{D_p}=\frac{1}{D_m}+\frac{1}{D_K}$$

$$D_m=\frac{0.926\times10^{-3}}{p_t}\left(\frac{T_a^{2.5}}{T_a+245}\right) \qquad D_k=97\gamma\left(\frac{T_a}{M_w}\right)^{1/2}$$

$$(1-\varepsilon)\frac{\partial}{\partial t}(\rho_d\omega_d)+\nabla\cdot\mathbf{j}_s=-\dot{m} \quad \text{Surface}$$

$$\mathbf{j}_s=-\frac{(1-\varepsilon)D_s}{\tau_s}\nabla(\rho_d\omega_d)$$

$$D_s=1.6\times10^{-6}\exp\left(-0.45\frac{h_{ads}}{R_w T_d}\right)$$

$$\varepsilon\frac{\partial}{\partial t}(\rho_a h_a)+\nabla\cdot\mathbf{q}_p+(\nabla\cdot\mathbf{j}_p)h_v=\dot{Q}+\dot{m}h_v \quad \text{pore}$$

$$\mathbf{q}_p=-\frac{\varepsilon k_a}{\tau_p}\nabla T_a \qquad q_c=\alpha(T_{ac,i}-T_{ac})$$

$$(1-\varepsilon)\frac{\partial}{\partial t}(\rho_d h_d)+\nabla\cdot\mathbf{q}_{sw}+(\nabla\cdot\mathbf{j}_s)h_w=-\dot{Q}-\dot{m}h_{ads}-\dot{m}h_w$$

$$\mathbf{q}_s=-\frac{(1-\varepsilon)k_{sw}}{\tau_s}\nabla T_d \quad \text{Surface}$$

$$\frac{\partial\rho_{ac}}{\partial t}+\frac{\partial\rho_{ac}u_{ac}}{\partial z}=\left(\frac{4}{d_h}\right)j_c$$

$$\frac{\partial\rho_{ac}w_{ac}}{\partial t}+\frac{\partial\rho_{ac}w_{ac}u_{ac}}{\partial z}=\left(\frac{4}{d_h}\right)j_c$$

$$\frac{\partial\rho_{ac}h_{ac}}{\partial t}+\frac{\partial\rho_{ac}h_{ac}u_{ac}}{\partial z}=\left(\frac{4}{d_h}\right)(q_c+j_c h_{vc})$$

$$j_c=\rho_{ac}\beta(w_{ac,i}-w_{ac})$$

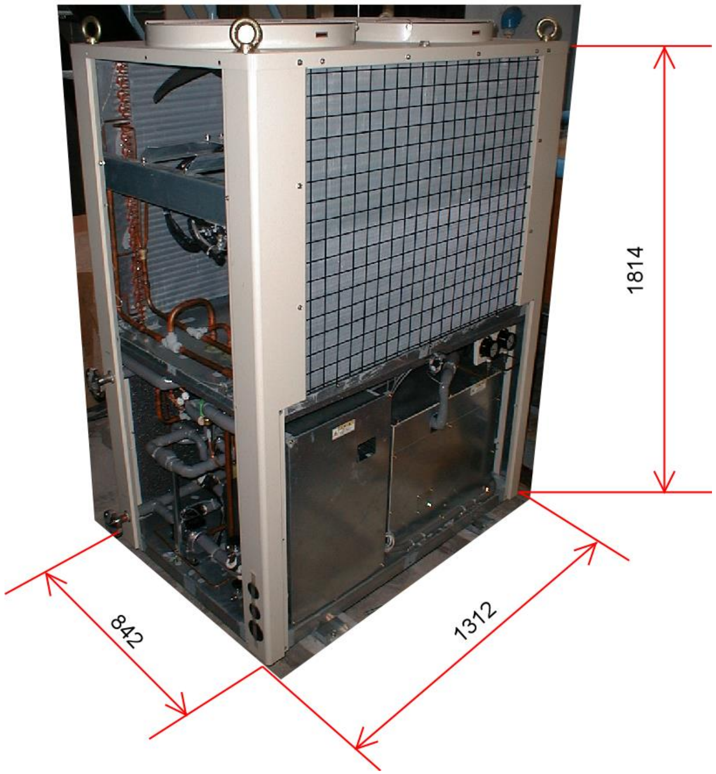
$$Nu=2.57+\sum_{i=0}^{3}a_i\left(\frac{z/d_h}{RePr}\right)^i\Bigg/\sum_{i=0}^{4}b_i\left(\frac{z/d_h}{RePr}\right)^i$$

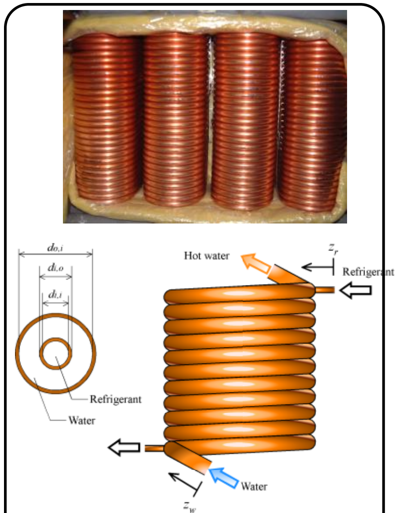
$$f\,\mathrm{Re}=52.96+\sum_{i=0}^{3}c_i\left(\frac{z/d_h}{Re}\right)^i\Bigg/\sum_{i=0}^{4}d_i\left(\frac{z/d_h}{Re}\right)^i$$

# EXAMPLE～$CO_2$ HEAT PUMP WATER HEATER

Feature:
Higher efficiency
Refrigerant is $CO_2$

SYSTEM

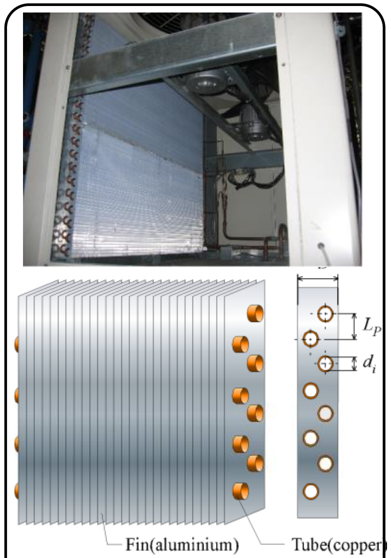



Gas cooler

Heat exchanger

Compressor




Evaporator

# SIMULATOR～ENERGY FLOW+M

We made internet and excel versions.

# VARIDATION

Simulation results are validated by **experiment** or **driving data** of actual system.

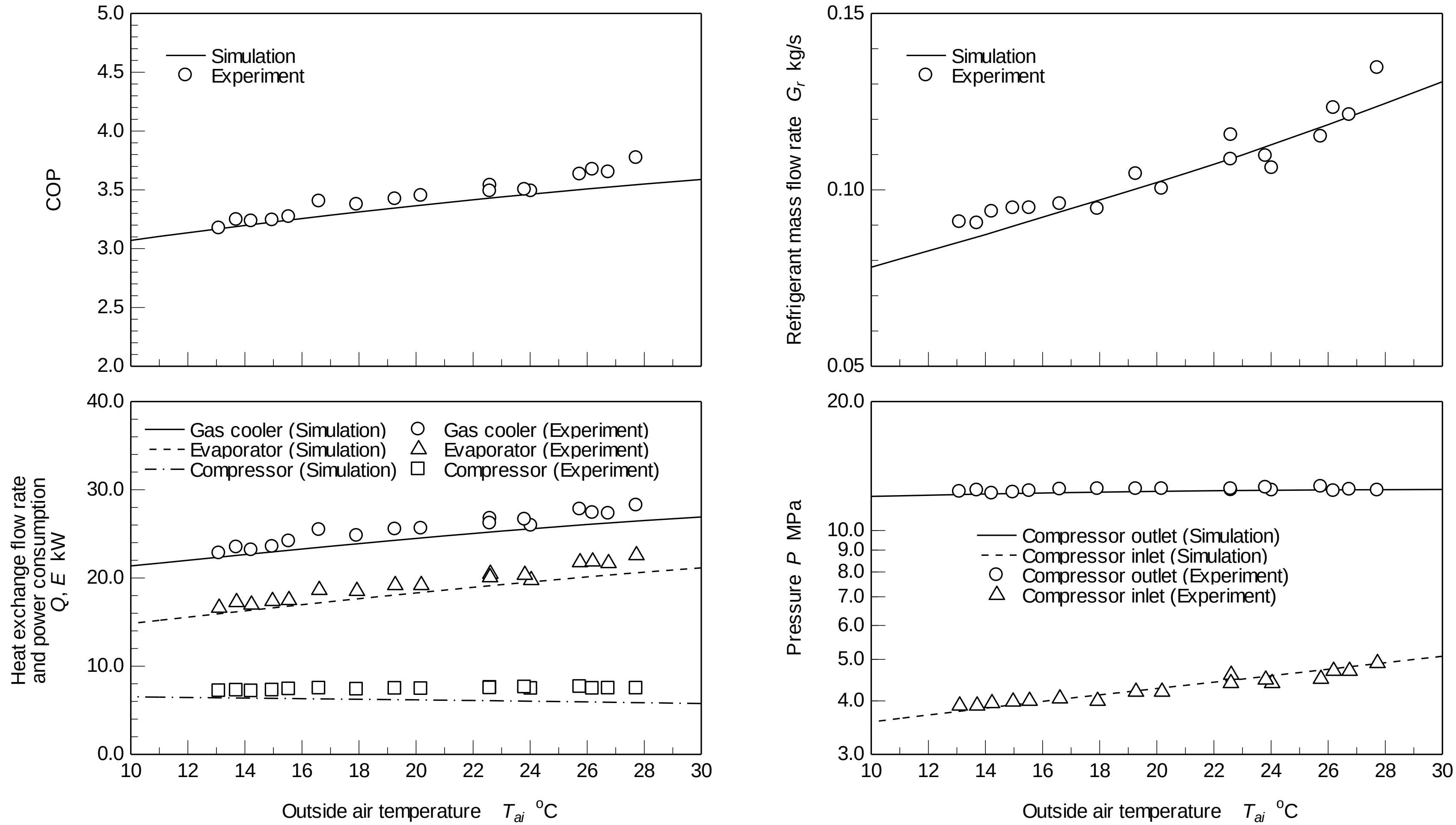


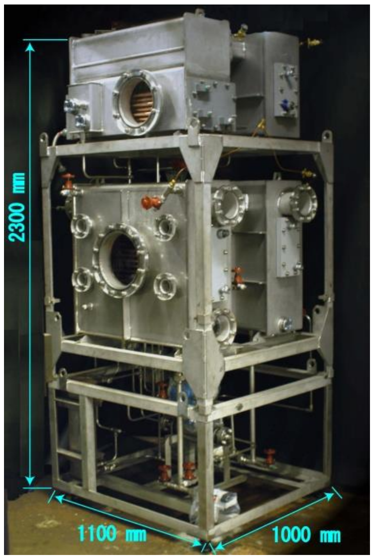

Fig. Simulation and experimental results for $CO_2$ heat pump system

# SYSTEMS WE CAN CALCULATE

We have already calculate heat pump, air-conditioner, absorption chiller, desiccant dehumidifier and solar thermal collector. More and more system simulator we are on developing.

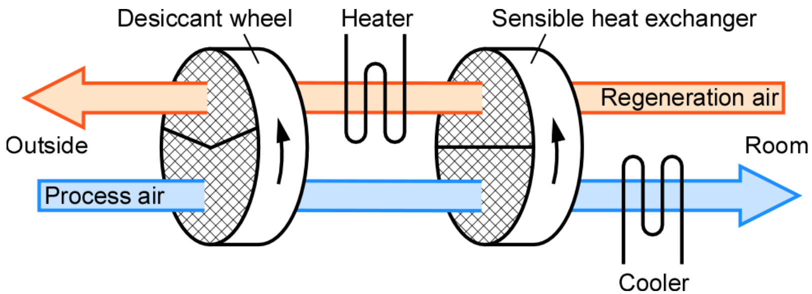
## Absorption chiller

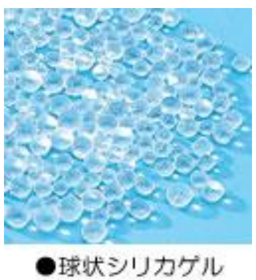
Feature:
Almost no electricity
Refrigerant is water
Driven by waste heat

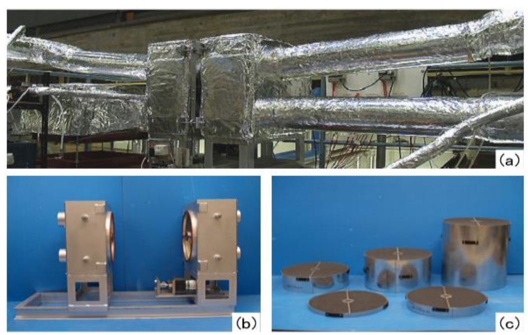



## Desiccant dehumidifier

Feature:
High performance dehumidification
working fluid is only air
Driven by waste heat.

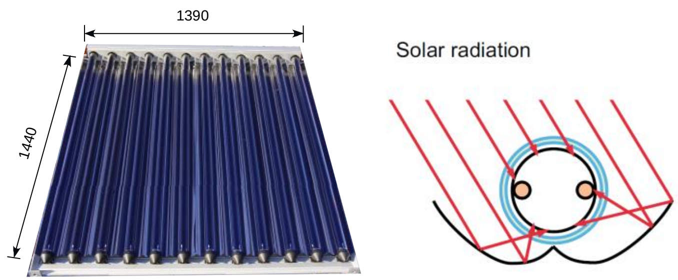



## Solar thermal collector

Feature:
High performance efficiency
Working fluid is water
Can drive heat driven system



# ADVANTAGE OF SIMULATOR

## KNOWLEDGE SPREAD OF NATURAL REFRIGERANT

Advantages of natural refrigerant use system for each countries' conditions are not well known yet. But people can easily know the best system or energy saving rate for each countries' situation without actual system introduction or test. This helps knowledge spread of natural refrigerant.

## COST REDUCTION

Since engineer can easily know design and driving method of natural refrigerant use systems that considers each countries' situation in detail, people can escape for example, over size system introduction and bad system driving. This leads to initial and running cost reduction.

## TRAINING AND EDUCATION

With this simulator, engineers, researchers and students can be easily trained in how to design and to drive natural refrigerant use systems without actual system introduction or test. This finally leads to cost reduction and speed up of natural refrigerant spread.

**"Simulator is very strong and essential tool in developing countries!!"**