Modelling and Control of High-Power Microelectronic Cooling

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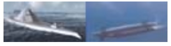
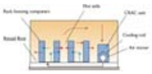
Cooling of High Power Electronic Systems

- **Application**
  - **Naval, air, and ground vehicles**
  - **Data centers**



Martin Cerza '04



Sharma, Bash, Patel, Friedrich, Chase '05 IEEE Internet Computing

- **Objectives**
  - **Removal of time-varying high heat flux to prevent burnout of electronic systems**
  - **Optimized design and operation of the cooling system for safety, efficiency, and robustness.**

Challenges

- **Difference from traditional refrigeration cycle:**
  - **Varying operating conditions: standby to full operation**
  - **Very high heat flux in certain operations**
  - **Transient, instead of steady-state, operation**
- **Multiple performance objectives and operating constraints**
- **Coupled, high order, and nonlinear model**

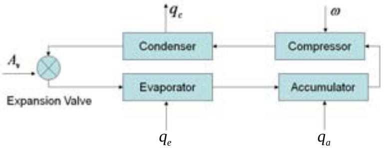
Proposed Solution and Approach

- **Refrigeration cycle with improved chip level heat transfer (thermal interface material, micro-channel)**
- **Model based analysis and optimization**
- **Experimental model calibration and validation**

Focus of Research

- **Steady-state analysis:**
  - **System architecture design and optimization (e.g., single vs. multiple loops)**
  - **Component sizing (e.g., compressor, accumulator)**
- **Dynamic model and control algorithm development**

Steady-state Analysis



- **Adjustable inputs:** evaporator heat flow rate (q_e), compressor speed (ω) and expansion valve opening (A_v).
- **Solve:** cycle steady state (pressure, enthalpy, q_c, q_a) for fixed (q_e, ω, A_v).

Steady-state Model

Steady-state mass, momentum, energy balance

evaporator

$$\left(\frac{\dot m}{A_e}\right)^2\left(\frac{1}{\rho(h_v,p_v)}-\frac{1}{\rho(h_e,p_e)}\right)-(p_e-p_v)-\Delta p_{fric,e}(h_v,p_v,\dot m,q_e)=0,$$
$$h_v=h_e-q_e/\dot m$$

condenser

$$\left(\frac{\dot m}{A_c}\right)^2\left(\frac{1}{\rho(h_m,p_m)}-\frac{1}{\rho(h_c,p_c)}\right)-(p_c-p_m)-\Delta p_{fric,c}(h_m,p_m,\dot m,-q_c)=0,$$
$$h_c=h_m-q_c/\dot m,$$
$$q_c=U_c\cdot S_c\cdot\left(\frac{T(h_m,p_m)+T(h_c,p_c)}{2}-T_{ocean}\right)$$

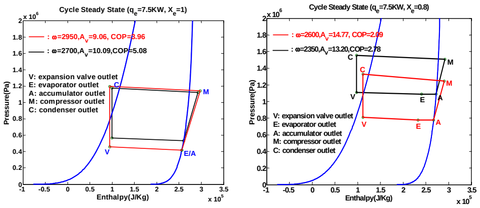
compressor

$$k=C_p(h_m,p_m)/C_v(h_m,p_m)$$
$$p_m=p_a\cdot\left(\frac{T(h_m,p_m)}{T(h_a,p_a)}\right)^{\left(\frac{k}{k-1}\right)},$$
$$h_m=h_a+W_{comp}/\dot m,$$
$$W_{comp}=f_W\left(T_{sat}(p_a),T_{sat}(p_m),\omega\right)$$
$$\dot m=f_m\left(T_{sat}(p_a),T_{sat}(p_m),\omega\right)$$

accumulator and expansion valve

$$p_a=p_e,\quad h_a=h_{sat}(p_a),$$
$$q_a=\dot m(h_a-h_e),$$
$$h_v=h_c$$
$$P_v=P_c-\left(\frac{\dot m}{K_vA_v}\right)^2\Big/\rho(h_c,P_c)$$

Steady-state Design Results

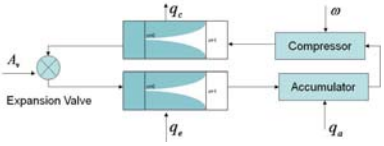


For given q_e (not considering Critical Heat Flux (CHF)), **lower compressor speed** (ω) and **higher exit quality** (x_e) lead to **higher power efficiency** for the cycle.

Active Charge of the Cycle

- Active charge: total mass in loop (evaporator, condenser, piping). Calculated based on density distribution.
- Different operations (q_e, ω, A_v) ➔ different amount of active charge. Worst case (maximum amount) active charge used to determine initial charge. Minimum active charge used to size accumulator (difference in charges for different operation conditions taken up by accumulator level adjustment).
- Current geometry: total volume of evaporator and condenser = 13in^3 ; volume of accumulator = 2827 in^3 (D_a=10 in, L_a=36in) ➔ active charge fluctuation resulting in negligible accumulator level change .

Dynamic Analysis



About an operating point,, dynamic control problems involve finding Av , ω to achieve

- Stability (convergence to steady state)
- Performance (rate of convergence)
- Disturbance rejection (change in q_e , q_c)
- Robustness (model uncertainty)

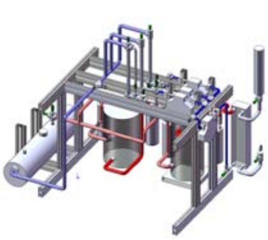
Dynamic Model

Balance equations for evaporator and condenser:

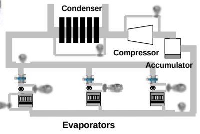
- Mass $$\frac{\partial\rho}{\partial t}+\frac{1}{A}\frac{\partial\dot m}{\partial x}=0$$
- Momentum $$\frac{1}{A}\frac{\partial\dot m}{\partial t}+\frac{1}{A^2}\frac{\partial}{\partial x}\left(\frac{\dot m^2}{\rho}\right)+\frac{\partial p}{\partial x}+\frac{\tau_w P}{A}=0$$
- Energy $$\frac{\partial\rho h}{\partial t}-\frac{\partial p}{\partial t}+\frac{1}{A}\frac{\partial\dot m h}{\partial x}+\frac{1}{2A^2}\frac{\partial}{\partial t}\left(\frac{\dot m^2}{\rho}\right)+\frac{1}{2A^3}\frac{\partial}{\partial x}\left(\frac{\dot m^3}{\rho^2}\right)=\frac{P_h q''}{A}$$

- **Dynamic components: evaporator and condenser**
  - **Variable lengths** of fluid regions (subcooled liquid, two-phase, superheated vapor).
  - **Lumped parameter approximation in each** region
- **Static components: compressor** and **expansion valve**

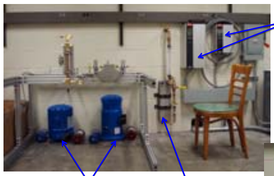
Experimental TestBed

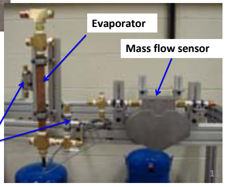


- **3 evaporators**
- **3 mass flow transducers**
- **6 diff. pressure sensors**
- **2 abs. pressure sensor**
- **12 temperature sensors**



Current Construction





Conclusion and Future Work

- Steady-state design and optimization
  - Steady-state design for components sizing and operation optimization: single evaporator, single vapor compressor loop
  - Extension: multiple evaporator, multiple loops
- Dynamic modeling and controller design
  - Low order linear model around steady state based on linearization and lumped model approximation
  - Linear controller design around steady state. Gain scheduling for nonlinear operation.
- Experimental testBed
  - Construction completion by May
  - Model calibration and validation, control experiments

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