Development of a Higher Fidelity Model for the Cascade Distillation Subsystem (CDS)

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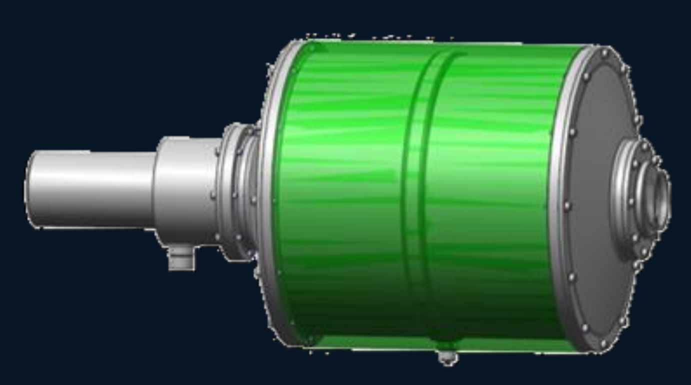
Background

Crewmembers require approximately 5 to 8 kg of water each per day during spaceflight. Therefore, significant mass and cost savings can be realized for long term missions by implementing systems to recycle wastewater into potable water. The **Cascade Distillation Subsystem (CDS)** is a next generation primary processor for wastewater recovery being developed through the Advanced Exploration Systems Program.

Aspen Custom Modeler (ACM) is a commercial software package that couples an equation solver to a chemical properties database, enabling dynamic simulation of specialized chemical processes. Individualized code is developed for each unit operation in the process. An initial model of the CDS was developed in ACM by Ramakumar Allada.



Rendering of the CDS

CDS Prototype

Objectives

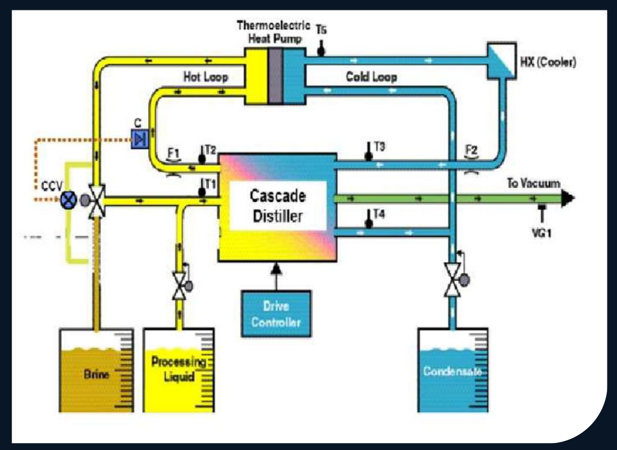
Improve upon the existing ACM model of the CDS and utilize the improved model to predict the effect of changing operating parameters on CDS performance:

- Reduce inputs to only measureable or controllable variables by developing analytical or empirical relationships for assumed/arbitrary parameters
- Improve fidelity of heat transfer analysis used in model
- Increase detail throughout the model
- Determine if key assumptions made about CDS operation are justified, and which areas of the model require further refinement
- Validate model by comparison to empirical data

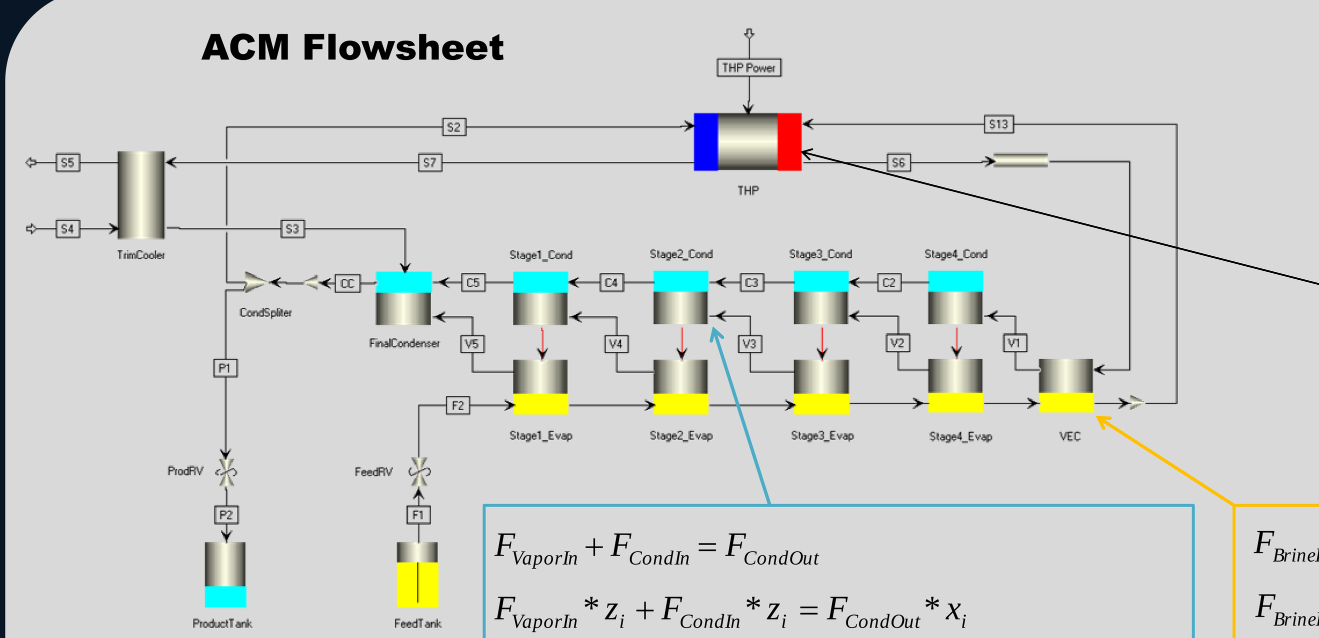
CDS Operating Theory

Separation in the CDS is based on vapor-liquid equilibrium thermodynamics, but it must operate in a microgravity environment. Unlike traditional distillation columns, which use gravity to separate vapor and liquid phases, the CDS uses a rotating drum to separate phases by centrifugal force.

- 5 stages
- Heat of vaporization recovered 4 times by heat transfer between evaporators and condensers
- Heating & cooling are provided by a thermoelectric heat pump (THP)
- Operated at low pressures to reduce heating duty



ACM Model Development



$$h_{HsideIn} * F_{HsideIn} + Q_h = h_{HsideOut} * F_{HsideOut}$$
$$h_{CsideIn} * F_{CsideIn} = h_{CsideOut} * F_{CsideOut} + Q_c$$
$$Q_h = Q_c + W$$
$$COP = \frac{Q_h}{W}$$

$$F_{VaporIn} + F_{CondIn} = F_{CondOut}$$
$$F_{VaporIn} * z_i + F_{CondIn} * z_i = F_{CondOut} * x_i$$
$$h_{CondIn} * F_{CondIn} + h_{VaporIn} * F_{VaporIn} = h_l * F_{CondOut} + Q + Q_{env}$$
$$Q = UA(T_{cond} - T_{evap})$$

$$F_{BrineIn} = F_{VaporOut} + F_{BrineOut}$$
$$F_{BrineIn} * z_i = F_{VaporOut} * y_i + F_{BrineOut} * x_i + n_L * \frac{dx_i}{dt}$$
$$h_{BrineIn} * F_{BrineIn} + Q = h_v * F_{VaporOut} + h_l * F_{BrineOut}$$
$$Q = UA(T_{cond} - T_{evap})$$

Key Model Variables

- **Inputs:** rotational speed, THP power, feed conditions, heat transfer coefficient scaling factor
- **Parameters:** heat transfer area, evaporator liquid holdup, evaporator-condenser pressure drop
- **Outputs:** temperatures, pressures & compositions throughout the system, product flow rate

Assumptions

Evaporators:
- Thermodynamic equilibrium between vapor and liquid
- Dynamic liquid phase mass and energy balances
- Constant liquid holdup

Condensers:
- Total condensation
- Psuedo-steady state mass and energy balances

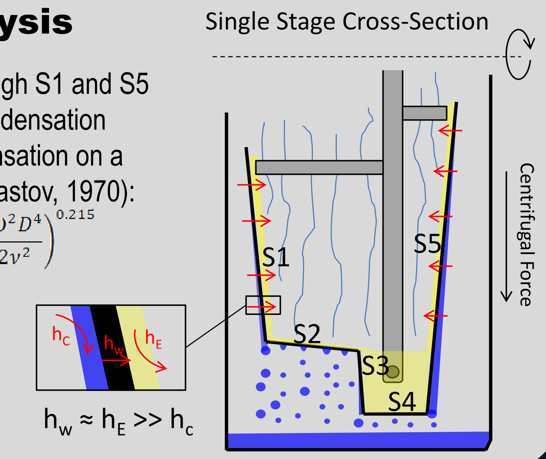
Heat Transfer Analysis

- Assumption: heat transfer through S1 and S5 dominates, but is limited by condensation
- Empirical correlation for condensation on a rotating disk (Astafiev and Baklastov, 1970):

$$h_{C,disk} = 1.38\left(\frac{\nu k^3 h_{fg}\rho_l}{D^4 \Delta T}\right)^{0.25}\left(\frac{\omega^2 D^4}{2\nu^2}\right)^{0.215}$$

- Scaling for rotational speed, diam., and ΔT input into ACM:

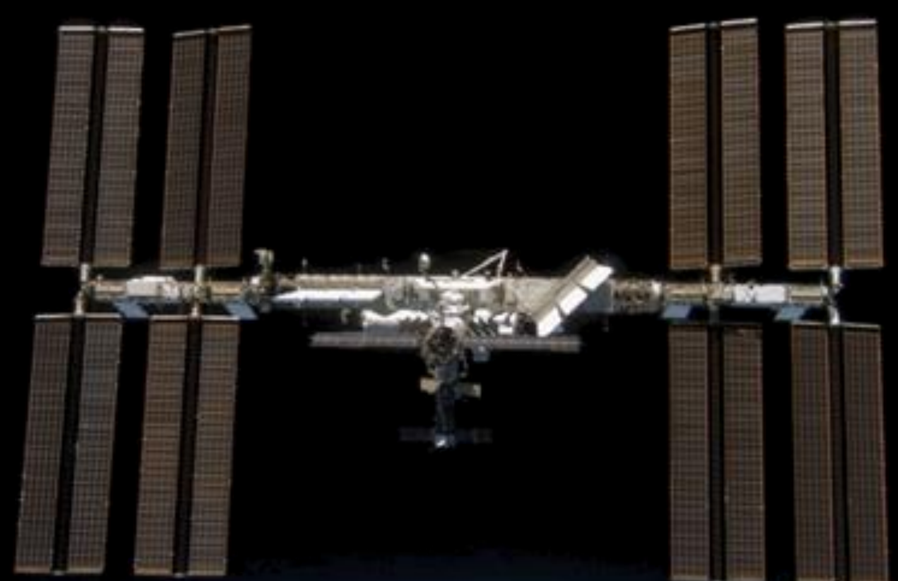
$$U = U_0 \frac{\omega^{0.43}}{D^{0.14}\Delta T^{0.25}}$$



Modifications to Original Model

Parameter	Pre-Existing Model	Modified Model
THP Coefficient of Performance	Estimated constant	Calculated from empirical correlation based on THP power, temps., flow rates
Distiller Motor Power Usage	Not Included	Variable, function of distiller rotation speed
Hot & Cold Loop Flow Rates	Estimated constant	Variable, function of distiller rotation speed
Heat Transfer Coefficient	Adjusted to fit data	Magnitude adjusted to fit data but scaling follows known correlations
Heat Transfer Area	Estimated constant	Determined from CDS dimensions
Evaporator Liquid Holdup	Estimated constant	Determined from CDS dimensions

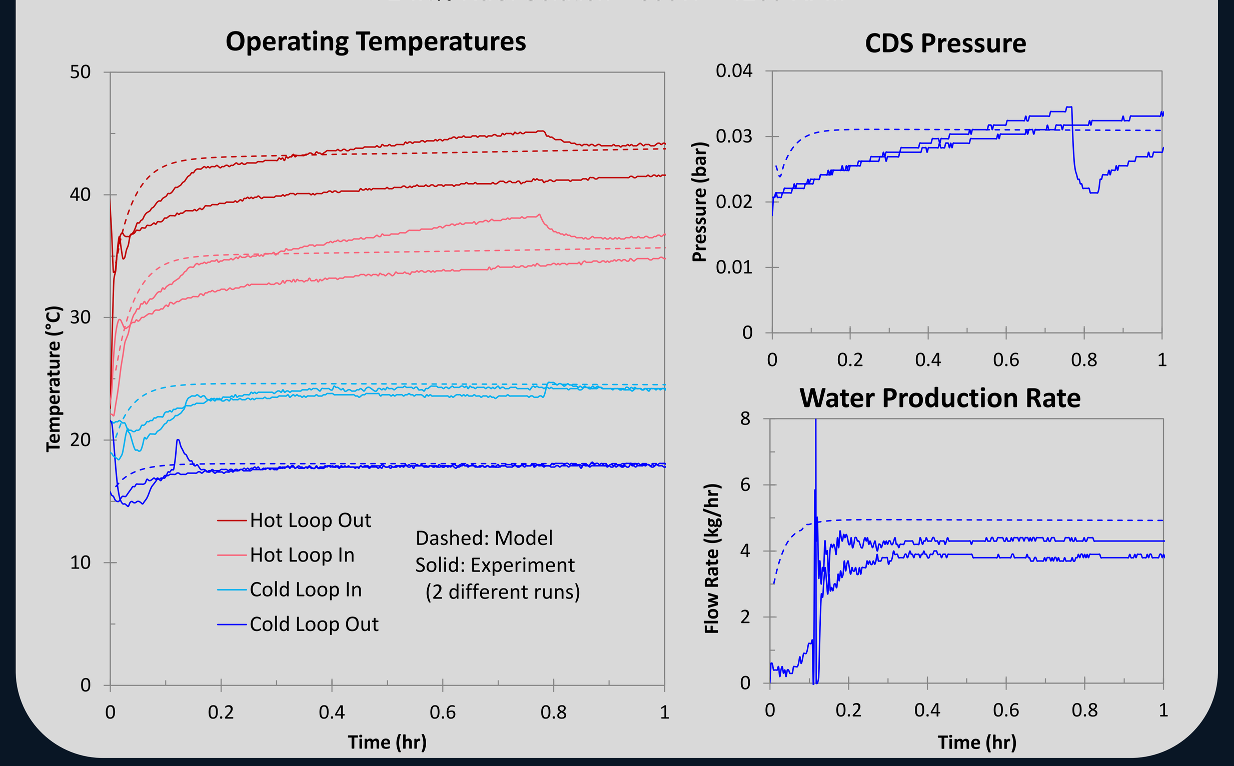
Capabilities added:
- Ability to model thermal startup
- Effect of inert dissolved gas in feed
- Modeling of pressure drop in vapor phase between evaporators and condensers
- Modeling of heat loss to surroundings



Results

Comparison: Model Predictions vs. Experimental Data

2 wt% NaCl Solution – 300W – 1200 RPM



Model Predictions

- Production rate is dependent on evaporator-condenser heat transfer
- Dissolved gasses increase steady operating pressures and temperatures, decreasing efficiency
- Heat loss to the environment has a negligible effect
- Pressure drop between stages significantly impairs performance
- Trade-off for increased THP power: increases production rate, but decreases efficiency
- Trade-off for increased rotational speed: increases flow rates, but also increases power consumption

Conclusions

Significant improvements have been made to the ACM model of the CDS, enabling accurate predictions of dynamic operations with fewer assumptions. The model has been utilized to predict how CDS performance would be impacted by changing operating parameters, revealing performance trade-offs and possibilities for improvement. CDS efficiency is driven by the THP coefficient of performance, which in turn is dependent on heat transfer within the system.

Based on the remaining limitations of the simulation, priorities for further model development include:
- Relaxing the assumption of total condensation
- Incorporating dynamic simulation capability for the buildup of dissolved inert gasses in condensers
- Examining CDS operation with more complex feeds
- Extending heat transfer analysis to all surfaces

Acknowledgements

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