Analysis of Water Vapor Condensation on Constellation Space Suit System Connectors

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CSAFE
New Suit New Team New Journey

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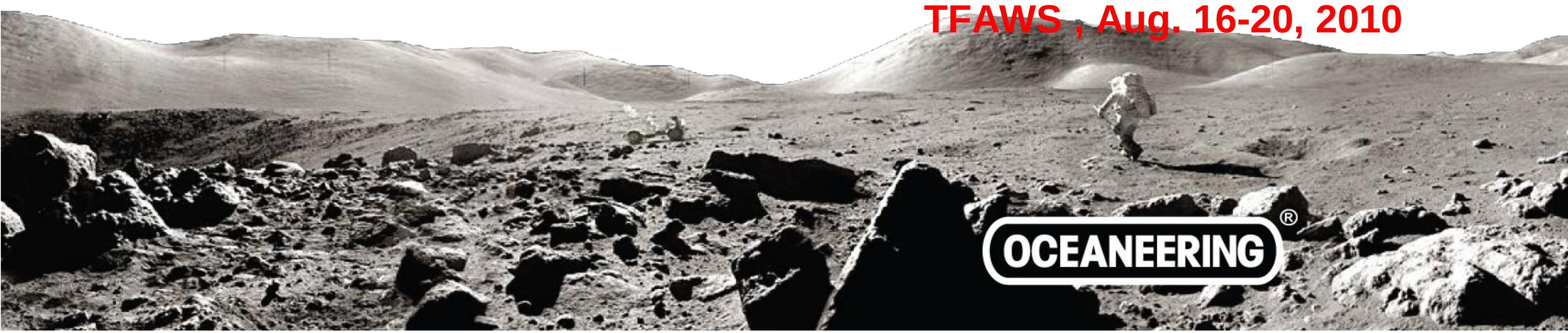
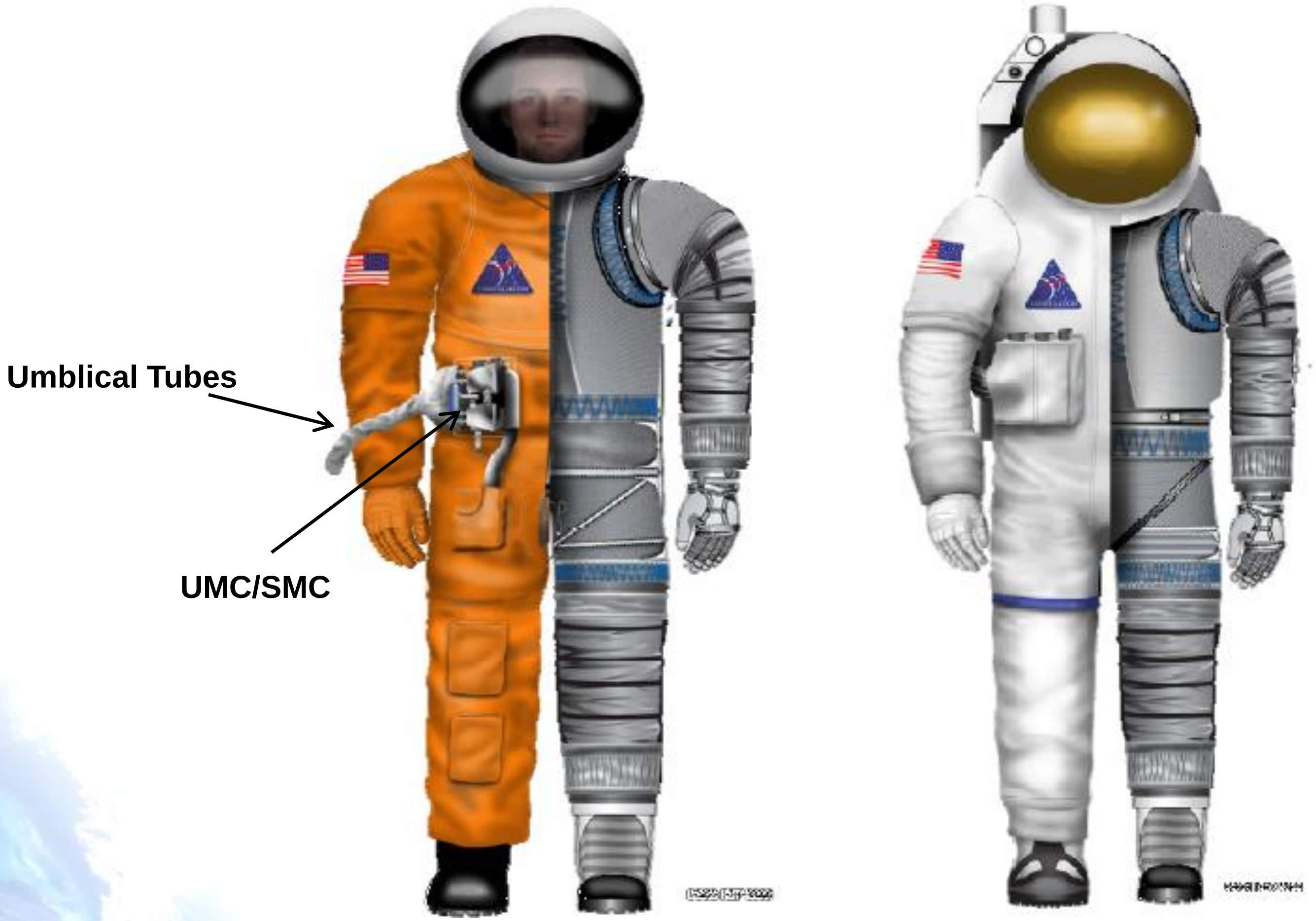


Objectives

- Develop a method to predict the water vapor condensation rate from the humid ambient air onto a cooled flat surface in a low gravity environment.

- Predict the water vapor condensation rate on Constellation Space Suit System (CSSS) connector surfaces for the worst case thermal conditions in the cabin (Orion) during donning/doffing of the spacesuit or a suited intra-vehicular activity (IVA).

Constellation Space Suit System



Launch/Entry/Abort &
Microgravity EVA Suit

Lunar Surface EVA Suit

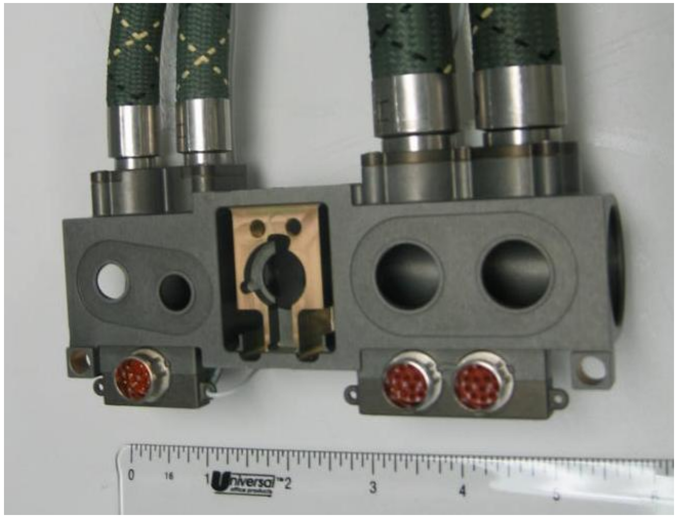
Oceaneering Space Systems is leading the effort to develop the next generation spacesuits for NASA. The figure shows the concepts of two spacesuit configurations.

CSSS Suit Multiple Connector and Umblical Multiple Connector

SAFE

SMC

UMC



The figures show the prototypes of the Suit Multiple Connector (SMC) and the Umblical Multiple Connector (UMC). The Vehicle Multiple Connector (VMC) (not shown) is similar to SMC. Cooling water and breathing air circulate from Orion to the spacesuit through the connectors and the umblical tubes.

SMC-UMC (mated)

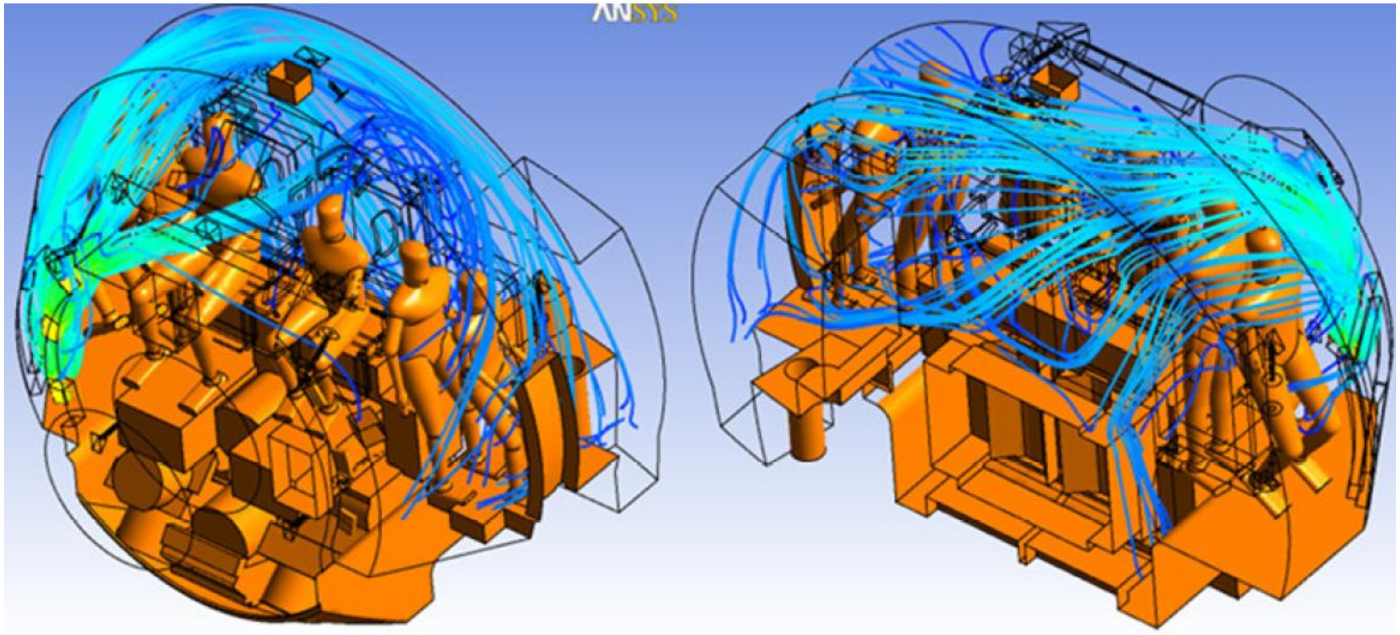
Steps to Predict the Water Vapor Condensation Rate on CSSS Connector Exterior Surfaces

1. Predict the air velocity and temperature distributions in the cabin using a CFD and heat transfer software such as ANSYS/Fluent for the given cabin airflow boundary conditions.

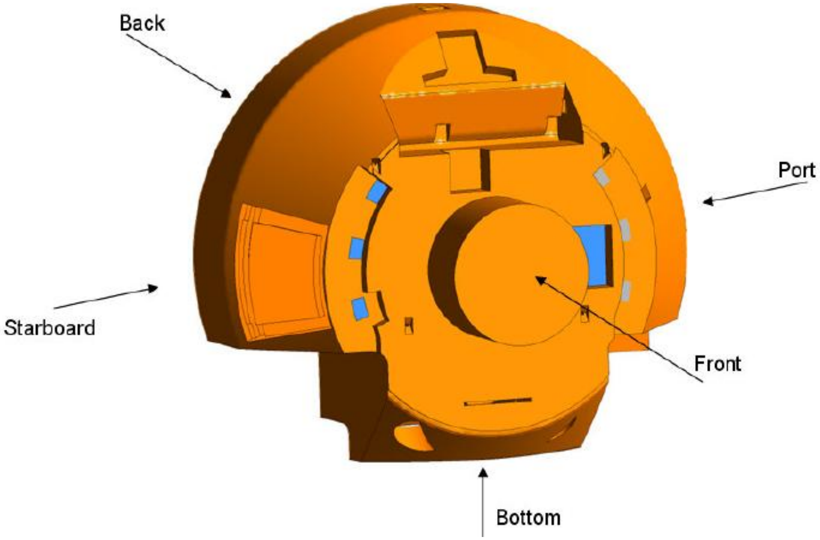
2. Predict the connector temperature distribution using a heat transfer software such as Thermal Analysis System (TAS) or ANSYS/Fluent for the given ambient airflow adjacent to the connector surfaces, and the cooling water and breathing air flows through the connectors.

3. **Predict the amount of water vapor condensation rate from the humid ambient air onto the cooled connector exterior surfaces for the given ambient airflow and connector surface temperature distributions.**

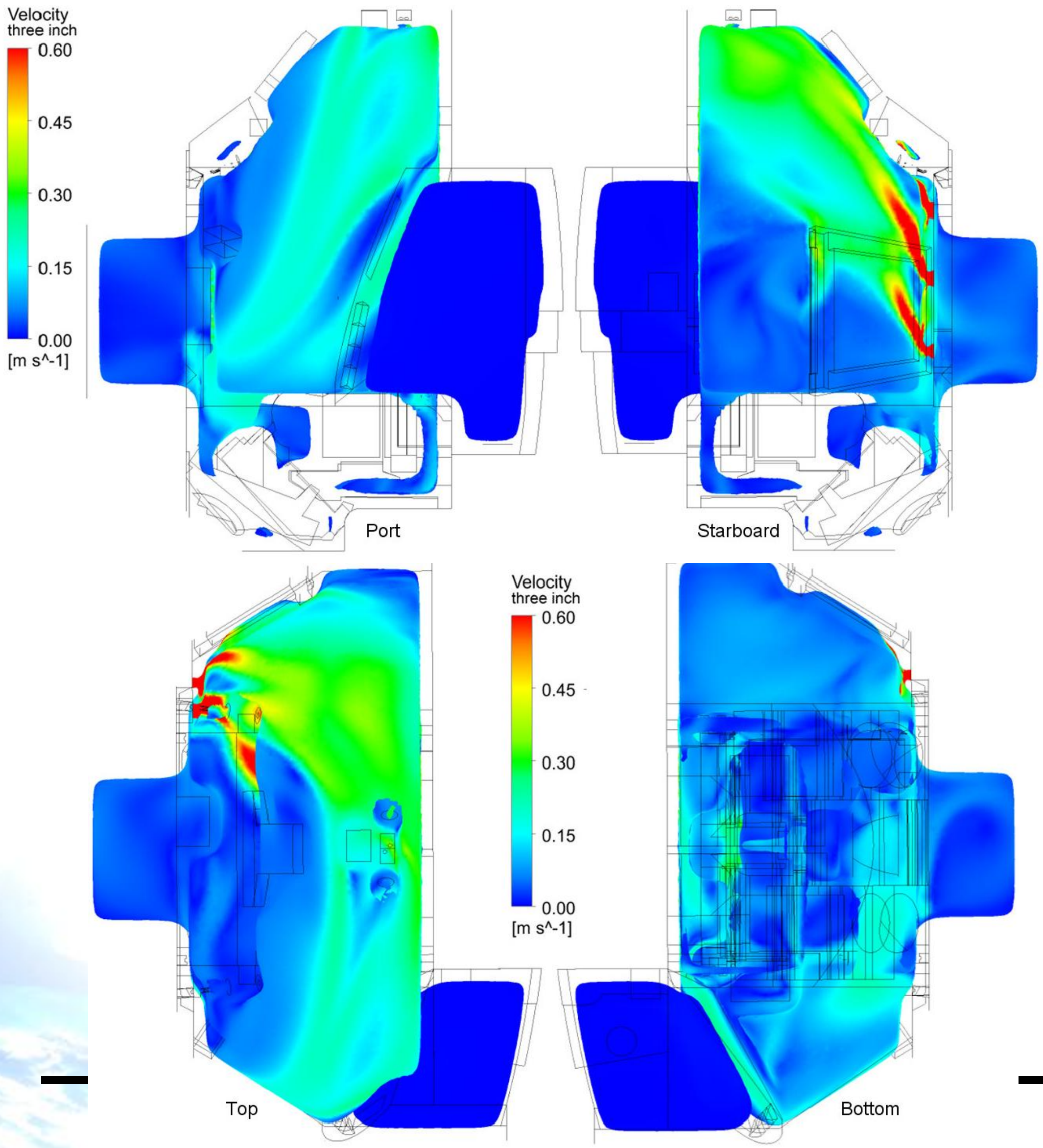
Typical Airflow Distribution in the Cabin from a CFD Analysis



Airflow at the cabin inlet=100 cfm.



Typical Airflow Distribution in the Cabin from a CFD Analysis (contd.)



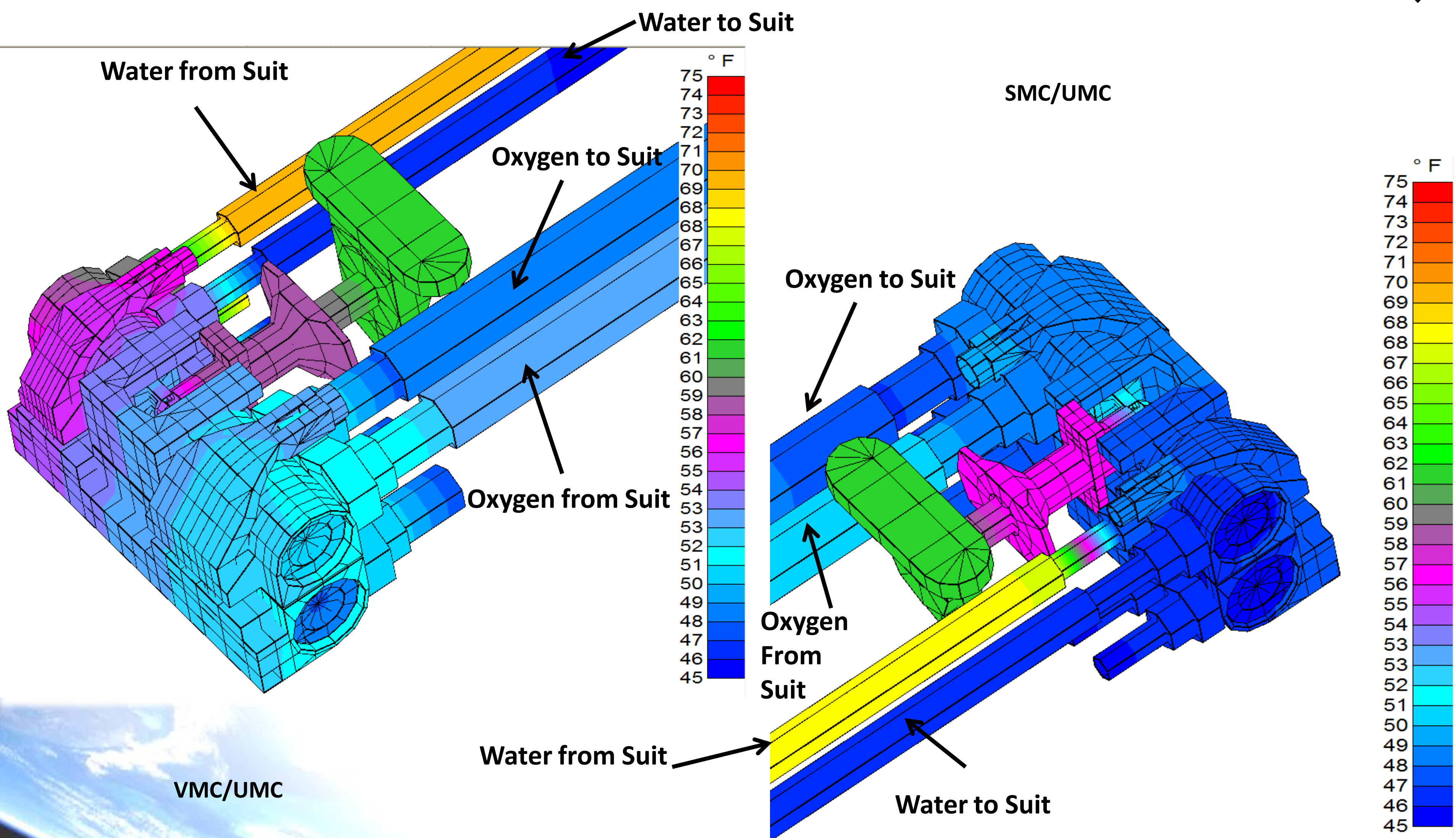
3" Offset Port and Starboard Views

Airflow at the inlet=100 cfm

3" Offset Top and Bottom Views

NEW SUIT
NEW TEAM
NEW JOURNEY

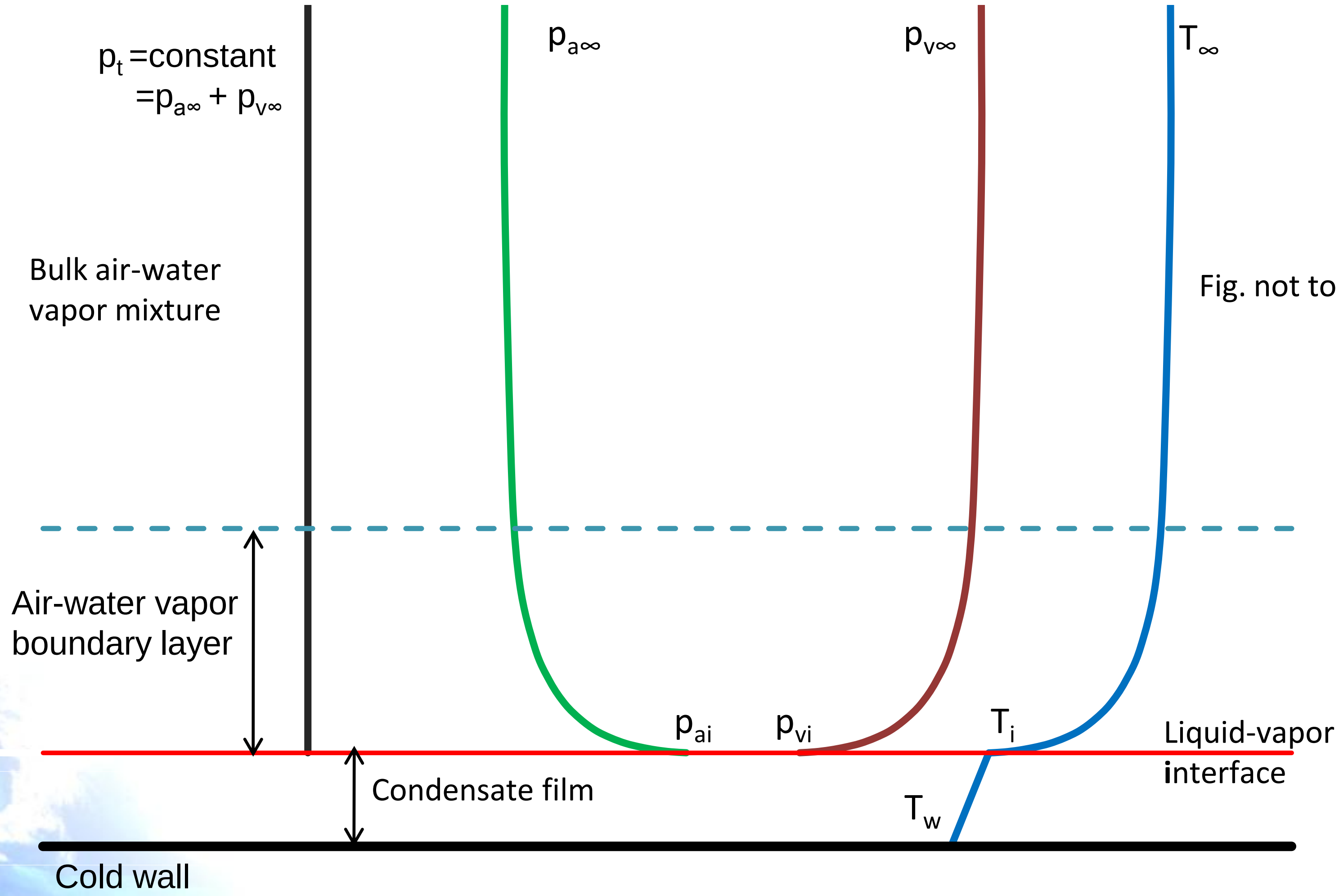
Typical Connector Surface Temperature Distribution from TAS Analysis



Condensate Rate Prediction Model Assumptions

- Crew cabin air is at standard composition and at 14.7 psi with a dew point temperature of 55 ^{o}F (worst case).
- Connector is in a low-gravity environment, and, therefore, the gravitational effects on the water vapor condensation are neglected.
- The airflow over the connector surfaces is laminar.
- The connector surfaces are assumed to be flat, and, therefore, irrespective of the connector orientation, the analysis of water vapor condensation on a cooled horizontal flat plate is valid for all the exposed connector surfaces.
- The condensate is assumed to be thin and stagnant, and, is of uniform thickness. (The drag due to the ambient airflow is neglected.)
- The liquid-vapor interface is assumed to be at saturation conditions.
- The condensate thickness on the wall is small (order of 1 mm).
- Water vapor condensation is mass transfer controlled.

Typical Profiles of Partial Pressures of Air and Water Vapor Over the Condensate and the Temperature Profile in the Air and in the Condensate



Water Vapor Condensation Rate Analysis Method

- Water vapor condensation is controlled by the water vapor mass flux through the air to the condensate-vapor interface. (→Need to know the interface temperature.)

- Heat balance at the condensate-air interface

$$q_w = q_{conv} + q_{conden} + q_{rad}$$

where $q_{conv} = -k_v(dT/dy)_i = h_t(T_\infty - T_i)$

$$q_{conden} = L_h(dm_v/dt)_i$$

$$q_{rad} = \varepsilon \sigma F_{12}(T_\infty^4 - T_i^4)$$

(Symbols are listed at the end of the presentation.)

- Conduction heat transfer analysis through the condensate,

$$q_w = -k_l\,(dT/dy)_w = k_l\,(T_i - T_w)/\delta \quad \text{(1-D linear)}$$

where δ is the condensate thickness (δ is small ~ 1 mm)

- Therefore, $k_l(T_i - T_w)/\delta = h_t(T_\infty - T_i) + L_h\,(dm_v/dt)_l + \varepsilon \sigma F_{12}(T_\infty^4 - T_i^4)$

→ $T_i = T_w + (\delta/k_l)[h_t(T_\infty - T_i) + L_h(dm_v/dt) + \varepsilon \sigma F_{12}(T_\infty^4 - T_i^4)]$

- Since the condensate thickness is assumed to be small (~ 1 mm), the second term on the RHS of equation is small, and, therefore, as a first approximation, T_i can be assumed to be equal to T_w to obtain the convective heat transfer coefficient from the ambient air to the condensate-vapor interface.

Water Vapor Condensation Rate Analysis Method (contd.)

- From the laminar forced convection heat transfer correlation, the average Nusselt number, Nu_L, over the flat plate is given by

$$Nu_L = 0.664 Re_L^{0.5} Pr^{0.333}$$

- The convection heat transfer coefficient from the air at the air-liquid interface is $h_t = Nu_L k/L$

- From heat and mass transfer analogy, the water vapor mass transfer coefficient, h_m, at the air-liquid interface is

$$h_t/h_m = \rho C_p Le^{2/3}$$

- As indicated earlier, the liquid-vapor interface temperature is very nearly at the wall temperature. Knowing the temperature, the saturation vapor pressure at the interface, can be obtained from literature (e.g. Arden Buck equation) and the water vapor density, $\rho_{vi,sat}$, from the ideal gas law.

- For the ambient conditions,

$$p_v = (RH)\, p_{v\infty,sat}$$

Water Vapor Condensation Rate Analysis Method (contd.)

where p_v and $p_{v\infty,sat}$ are the water vapor pressure and the saturation vapor pressure at the ambient conditions, respectively, and RH is the relative humidity of the ambient air. Knowing p_v and assuming that the water vapor behaves like an ideal gas, the water vapor density at the ambient conditions, $\rho_{v\infty}$, can be found from the ideal gas law (or from steam tables).

- The water vapor mass flux to the air-liquid interface, m_v, is then given by

$$m_v = h_m(\rho_{v\infty} - \rho_{vi,sat})$$

- The total mass transfer rate from the connector surface, M_v (kg/s), is given by

$$M_v = m_v A$$

where A is the area of the liquid-vapor interface. When the entire connector surface temperature is lower than the dew point temperature, A is same as the connector surface area exposed to the ambient air.

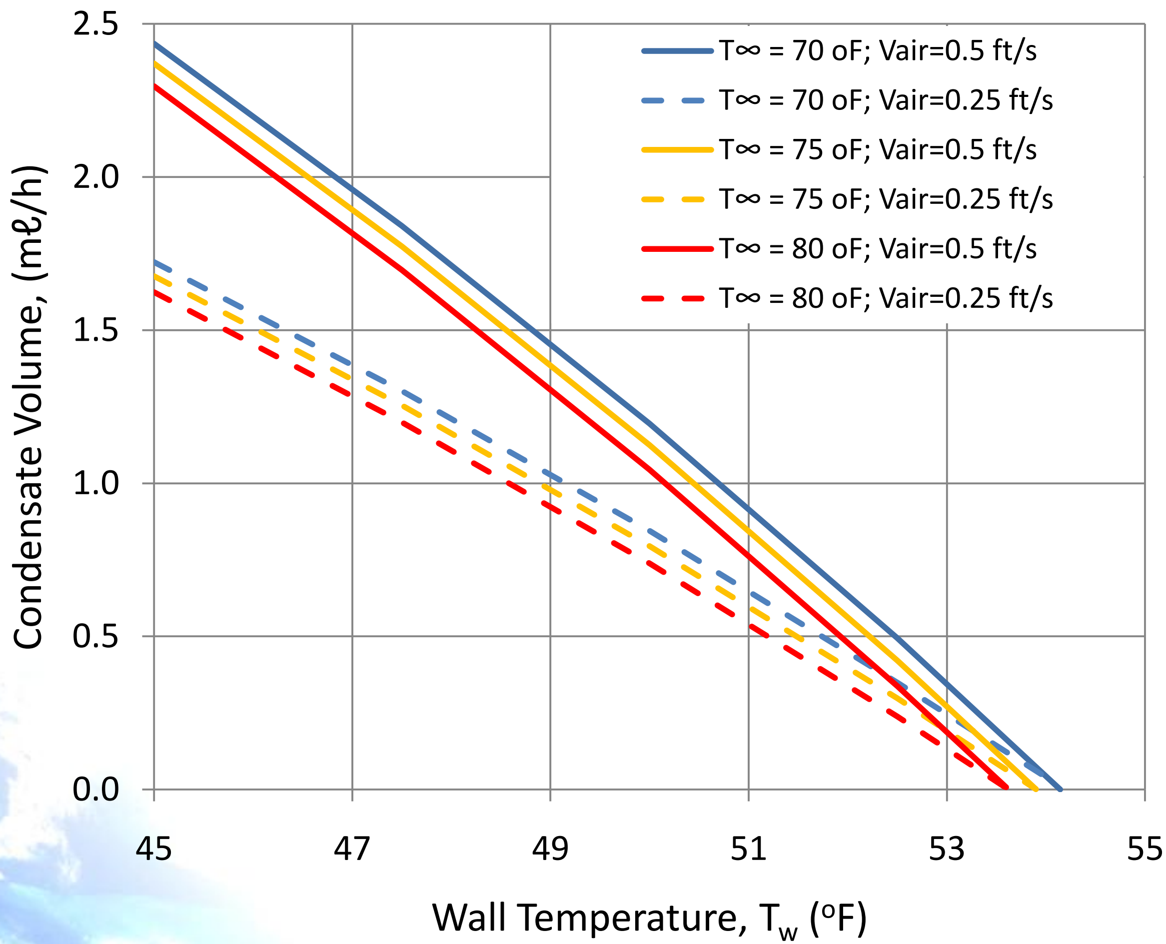
Water Vapor Condensation Rate Analysis Method (contd.)

For a typical condition considered in this study,

T_w = 45 °F (=7.22 °C)
T_∞ = 70 °F (=21.11 °C)
RH = 58.9%
u_∞ = 0.5 ft/s (=0.15 m/s)
L = 6 in (=0.15 m)
Pr = 0.73
Le = 0.86
Re_L = 1550 (→ laminar flow)
Nu_L = 23.3
h_t = 3.9 W/(m²K)
h_m = 0.0035 m/s
m_v = 10.5×10^{-6} kg/(m²s)
q_{conv} = 51 W/m²
q_{conden} = 26 W/m²
q_{rad} = 73 W/m² (for $F_{12}=1=\varepsilon$)
δ = 1 mm (assumed)
(T_i-T_w) = 0.27 °C

Water vapor condensation rate=2.44 mℓ/h

Predicted Water Condensate vs. Wall Temperature



Connector length= 6 in
Wall surface area= 100 in^2
Ambient air pressure=14.7 psi
Dew point temperature = 55 ^oF

Conclusions

- A method to predict the water vapor condensation rate from the humid ambient air onto a cooled flat surface in a low gravity environment was developed.

- The method was applied to predict the water vapor condensation on CSSS VMC, UMC and SMC surfaces for the worst case thermal conditions in the cabin during donning/doffing the spacesuit or a suited IVA.

- The water vapor condensation rate decreases with an increase in connector surface temperature and a decrease in air velocity adjacent to the connector surface.

- The predicted water vapor condensation on a VMC/UMC or UMC/SMC combination cooled with water at 45 ^{o}F in an ambient air at 70 ^{o}F with a dew point temperature of 55 ^{o}F was about 2.4 mℓ/h (or 58 mℓ/day).

- The method can be extended to predict water vapor condensation to similar situations such as water vapor condensation over the cooled umbilical tubes so long as the thickness of the condensate is small compared to the tube diameter.

Symbols:

A = wall (connector) surface area
C_p = specific heat of air
D_{AB} = binary diffusion coeff. of water vapor in air
F_{12} = view factor
h_t = heat transfer coeff. at liquid-vapor interface
h_m = mass transfer coeff. at liquid-vapor interface
k_l = condensate thermal conductivity
L = connector length
Le = Lewis number
L_h = Latent heat of condensation
m_v , M_v = water vapor condensation mass flux
Nu_L = Nusselt number
Pr = Prandtl number
q_{conden}= heat transferred by condensation
q_{conv}= heat transferred by convection
q_{rad} = heat transferred by radiation

Re_L = Reynolds number
RH = relative humidity of air
T_w = wall temperature
T_∞ = ambient air temperature
T_i = liquid-vapor interface temperature
y = distance (normal) from the liquid-vapor interface
u_∞ = ambient air velocity adjacent to the connector surface
ε = connector surface emissivity
σ = Stefan-Boltzmann constant
δ = condensate thickness
$\rho_{vi,sat}$= saturation density of water vapor at liquid-vapor interface
$\rho_{v\infty}$ = density of water vapor at ambient conditions

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