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# Dynamic Modeling of Inbreathing Requirements for Low Pressure Storage Tanks

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# We will cover the following topics in this short presentation

- Overview of current standards used for calculating relief requirements due to thermal inbreathing
- Previous work on thermal inbreathing for low-pressure storage tanks
- Effect of vapor condensation on thermal inbreathing requirements
- A brief introduction to Process Safety Office® SuperChems™ wall dynamics for vapor and two-phase systems
- SuperChems™ model validation vs. measurements and other published simulation results
- SuperChems™ relief requirements prediction vs. API 2000 equations for condensable vapors

# This presentation is based on recent ioMosaic sponsored research at Northeastern University in 2016

- Research was supervised by Dr. Ronald Wiley and Dr. G. A. Melhem
- Funded by ioMosaic
- A primary objective of this research was to qualify existing methods for the proper prediction of relief requirements under extreme weather conditions for low-pressure storage tanks including the impact of condensable vapor and mixtures with wide boiling points
- The second objective of this research was to qualify the impact of solar flux on outbreathing and inbreathing at different locations around the globe
- A third objective was to compare the detailed SuperChems™ wall dynamics single-phase and two-phase models vs. large scale test data and other researchers recent work and to establish reasonable and recommended values for heat transfer coefficient (rain and wall-vapor)

# Relief and vacuum protection requirements for low pressure tanks are addressed by API-2000

- **Causes of Vacuum as stated in API 2000**:
  - 3.2.3. Weather Changes:
    - Vacuum can result from the contraction or condensation of vapors caused by a decrease in atmospheric temperature or other weather changes, such as wind changes, precipitation, etc. Overpressure can result from the expansion and vaporization that is caused by an increase in atmospheric temperature or weather changes. See 3.3 for calculation methods.
  - 3.2.5.13 Steam Condensation
    - If an uninsulated tank is filled with steam (e.g. for steam-out decontamination), the condensing rate due to ambient cooling can exceed the venting rates specified in this standard. Procedures, such as the use of large vents (open manways), controlling the tank cooling rate, or adding a non-condensable gas such as air or nitrogen, are often necessary to prevent an excessive internal vacuum.
  - 3.2.5.14 Uninsulated Hot Tanks
    - Uninsulated tanks with exceptionally hot vapor spaces can exceed the thermal inbreathing requirements in this standard during a rainstorm. Vapor contraction and/or condensing can cause an excessive vacuum. An engineering review of heated, uninsulated tanks with vapor-space temperatures above 48.9° C (120° F) is recommended.

Source: API 2000

# Simple formulas for the thermal in-breathing requirements for low pressure tanks is provided by API 2000

$$\dot{V}_{IT} = C\ V_{tk}^{0.7} R_i$$

$\dot{V}_{IT}$ = Maximum inbreathing volumetric flow rate of air at normal conditions in $m^3/h$

$V_{tk}$ = Tank volume in $m^3$

$R_i$ = Reduction factor for insulation, 1 where tank is not insulated

$C$ = Dimensionless factor which depends on storage temperature, vapor pressure and latitude

| Latitude, φ | C-factor | | | |
|---|---|---|---|---|
| | Vapor pressure similar to hexane | | Vapor pressure higher than hexane or unknown | |
| | Average storage temperature (°C) | | | |
| | < 25 | ≥ 25 | < 25 | ≥ 25 |
| $\varphi < 42^o$ | 4 | 6.5 | 6.5 | 6.5 |
| $42^o \le \varphi \le 58^o$ | 3 | 5 | 5 | 5 |
| $\varphi > 58^o$ | 2.5 | 4 | 4 | 4 |

Source: API 2000

# There are some key assumptions used by API 2000 for inbreathing requirements

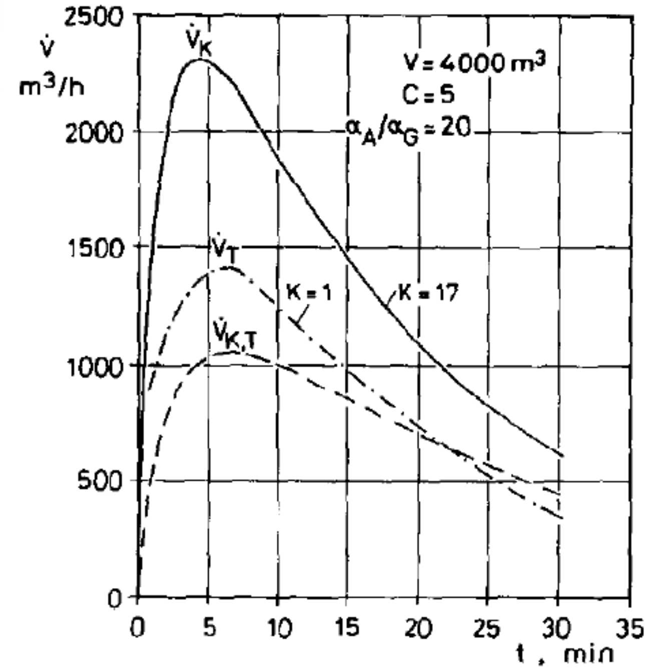
- Tank is filled with dry air only
- Initial contents and wall temperature = 55° C
- Constant rain properties
  - Rain flow density = 225 kg/m2h or 225 mm/h (8.86 in/h)
  - Rain angle = 30 degrees with vertical
  - Rain water temperature 15° C
- Natural convection of vapor to wall; $h_{gas}$ = 5 $W/m^2/K$
- Film cooling on the tank outer shell; $h_{rain}$= 5,000 $W/m^2/K$

# There are some potential shortcomings of the API 2000 Equation

- Applicable to only non-condensable gases
- Constant heat transfer coefficients of natural convection inside the tank
- Single volume (lumped capacitance) approach
- Only vapor phase exists in the tank
- Focuses on gases similar to hexane service

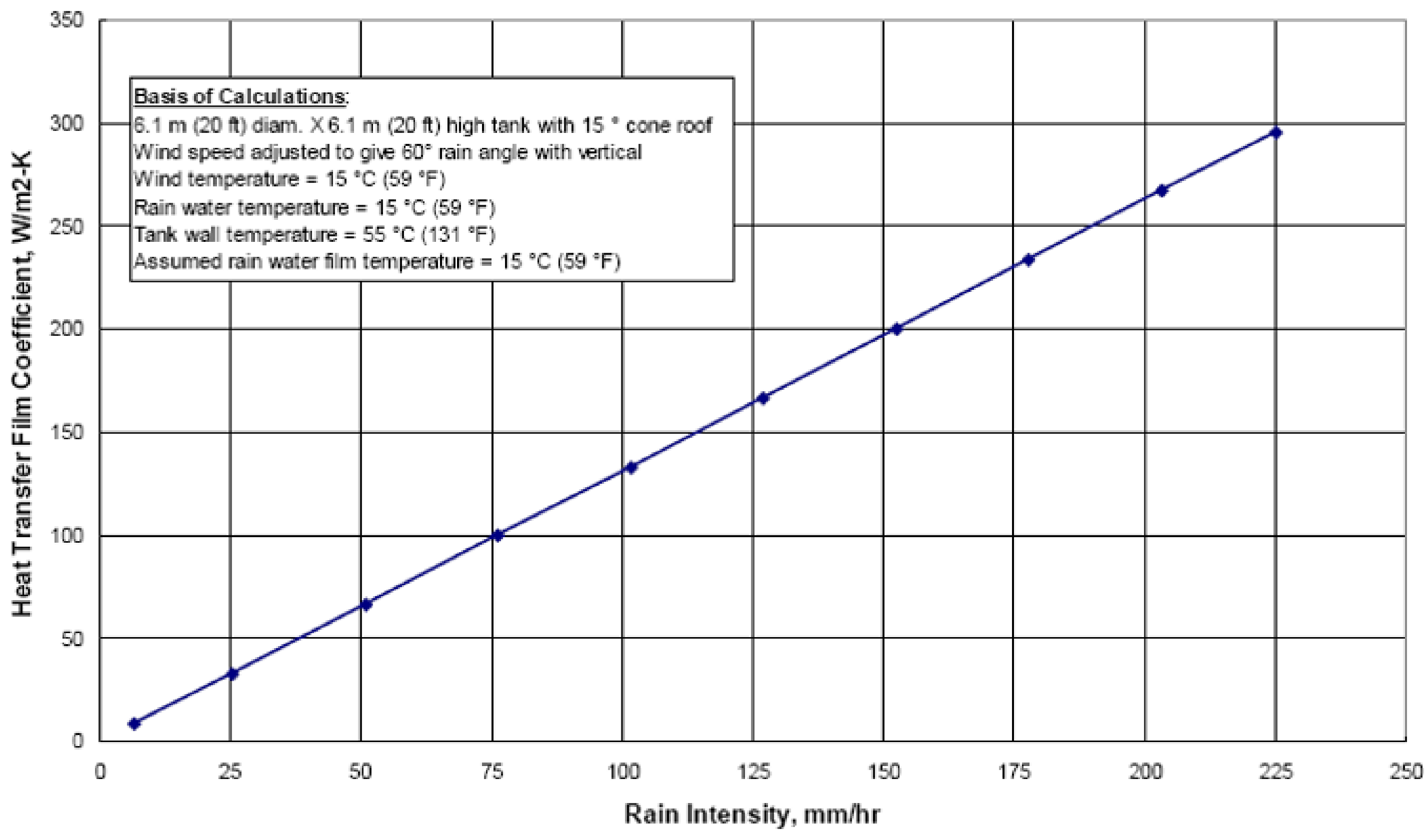
# The impact of condensation on inbreathing requirements has already been identified in the literature

- Fullarton (1986)
  - Accounted for the heat of condensation released at the inside shell wall
  - Considered the heat capacity of the tank wall
  - Defined 2 factors: reduction and condensation
- Protego simulations and dynamic modeling
  - Simulated Fullarton's tank (water vapor)
  - Simulated case studies of 5 different vapors: methanol, ethanol, heptane, decane, and water




Source: Fullarton, D. "Influence of Product Vapour Condensation of Venting of Storage Tanks" (1986)

# Brooks (2012) published a very useful summary and analysis of the rain to wall heat transfer coefficient which was implemented in SuperChems™ v8.1




Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# There are some differences regarding the recommended value of the rain heat transfer coefficient to use

| Rainstorm Type | API 2000 | Brooks 2012 | Protego | | Fullarton 1986 |
|---|---|---|---|---|---|
| Average; 1/year | N/A | N/A | 37 W/m$^2$K | 75 kg/m$^2$h | 25 W/m$^2$K |
| Heavy; 1/20 years | N/A | 50 W/m$^2$K | 50 W/m$^2$K | 150 kg/m$^2$h | 50 W/m$^2$K |
| Unrealistic Downpour; 1/100 years | 225 kg/m$^2$h | 356 W/m$^2$K | 500 W/m$^2$K | 225 kg/m$^2$h | N/A |

# Tank wall metal thickness is important because thicker walls have a larger thermal capacity than thinner walls

- Thickness according to tank diameter. All the tanks we're using have a diameter less than 30 m hence **5 mm** was the chosen as the wall thickness

DIN 4119 (Annex E) - Minimum Wall Thickness

| | |
|---|---|
| $d_M = 5$ mm | $D \leq 30$ m |
| $d_M = 6$ mm | $30\text{ m} < D \leq 40$ m |
| $d_M = 7$ mm | $40\text{ m} < D \leq 50$ m |
| $d_M = 8$ mm | $50\text{ m} < D \leq 60$ m |
| $d_M = 9$ mm | $60\text{ m} < D$ |

Source: PTB

# We found very few good large scale data sets

- Large scale test data is preferred for model validation and enables
- Free convection heat transfer coefficient according to gas' volatility
- Impact of storing mixtures with wide boiling points

# Our SuperChems™ modeling simulations have the following assumptions

- Tank wall is divided into 5 segments
- Initial liquid level = 0.1%
- Fix the outside (rain) heat transfer coefficient to 50 $W/m^2K$
- Rain duration = 30 minutes
- Ambient temperature = 15° C

# The SuperChems™ two-phase vessel contents mass and energy balances are very detailed

*Energy*

$$\left[N_{\text{internals}} C_{v_{\text{internals}}} + \sum_i^C (N_i + n_i) C_{v_i} + N_T \frac{\partial \Delta \underline{U}_v}{\partial T} + n_T \frac{\partial \Delta \underline{U}_l}{\partial T}\right] \frac{dT}{dt} \quad +$$

$$\left[N_T \frac{\partial \Delta \underline{U}_v}{\partial P} + n_T \frac{\partial \Delta \underline{U}_l}{\partial P}\right] \frac{dP}{dt} \quad +$$

$$\sum_i^C \left(\underline{U}_{i,ref} + \int_{T_{ref}}^{T} C_{v_i} dT + \Delta \underline{U}_v + N_T \frac{\partial \Delta \underline{U}_v}{\partial N_i}\right) \frac{dN_i}{dt} \quad +$$

$$\sum_i^C \left(\underline{U}_{i,ref} + \int_{T_{ref}}^{T} C_{v_j} dT + \Delta \underline{U}_l + n_T \frac{\partial \Delta \underline{U}_l}{\partial n_i}\right) \frac{dn_i}{dt} \quad =$$

$$\dot{Q} - \dot{H}_{l,out} - \dot{E}_{l,out} - \dot{H}_{v,out} - \dot{E}_{v,out}$$

*Don't forget PVT!*

*Mass*

$$\frac{dn_i}{dt} + \frac{dN_i}{dt} = -\dot{n}_{i,out} - \dot{N}_{i,out} + \dot{R}_i \quad (\text{for } i = 1, \cdots, C)$$

*Volume*

$$(V_v \beta_v + V_l \beta_l) \frac{dT}{dt} - (V_v \kappa_v + V_l \kappa_l) \frac{dP}{dt} + \sum_i \overline{V}_{v_i} \frac{dN_i}{dt} + \sum_i \overline{V}_{l_i} \frac{dn_i}{dt} = 0$$

*Phase Equilibrium*

$$\frac{N_i}{N_T} - \frac{n_i}{n_T} \frac{\hat{\phi}_{l,i}}{\hat{\phi}_{v,i}} = 0 \quad (\text{for } i = 1, \cdots, C)$$

Source: Brooks, D. "Thermal Inbreathing Requirements of Low Pressure Storage Tanks at Elevated Temperatures" (2012)



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# The SuperChems™ two-phase balances can be simplified for vessels containing vapor or supercritical fluids

Don't forget PVT!

**Energy**

$$a\frac{dT}{dt} + b\frac{dP}{dt} = c$$

where $a$, $b$, and $c$ are constants defined as follows:

$$a = N_{\text{internals}} C_{v_{\text{internals}}} + \sum_{i}^{C} N_i C_{v_i} + N_T \frac{\partial \Delta \underline{U}_v}{\partial T}$$

$$b = N_T \frac{\partial \Delta \underline{U}_v}{\partial P}$$

$$c = \dot{Q} - \dot{H}_{v,out} - \dot{E}_{v,out} - \sum_{i}^{C} \left( \underline{U}_{i,ref} + \int_{T_{\text{ref}}}^{T} C_{v_i} dT + \Delta \underline{U}_v + N_T \frac{\partial \Delta U_v}{\partial N_i} \right) \frac{dN_i}{dt}$$

**Mass**

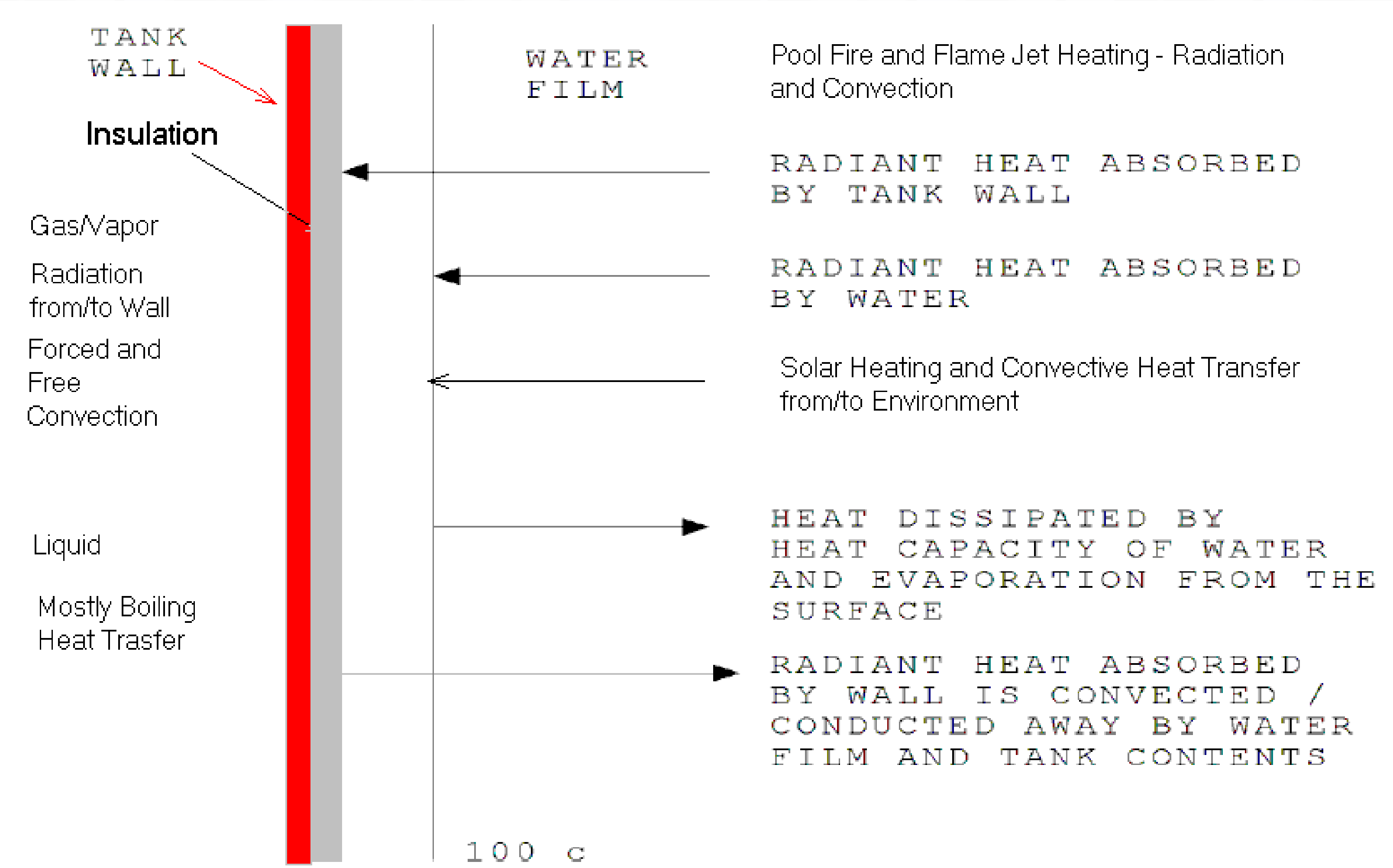
$$\frac{dN_i}{dt} = -\dot{N}_{i,out} + \dot{R}_i \quad (\text{for } i = 1, \cdots, C)$$

**Volume**

$$\beta_v \frac{dT}{dt} - \kappa_v \frac{dP}{dt} = -\frac{1}{V_v} \sum_i \overline{V}_{v_i} \frac{dN_i}{dt}$$

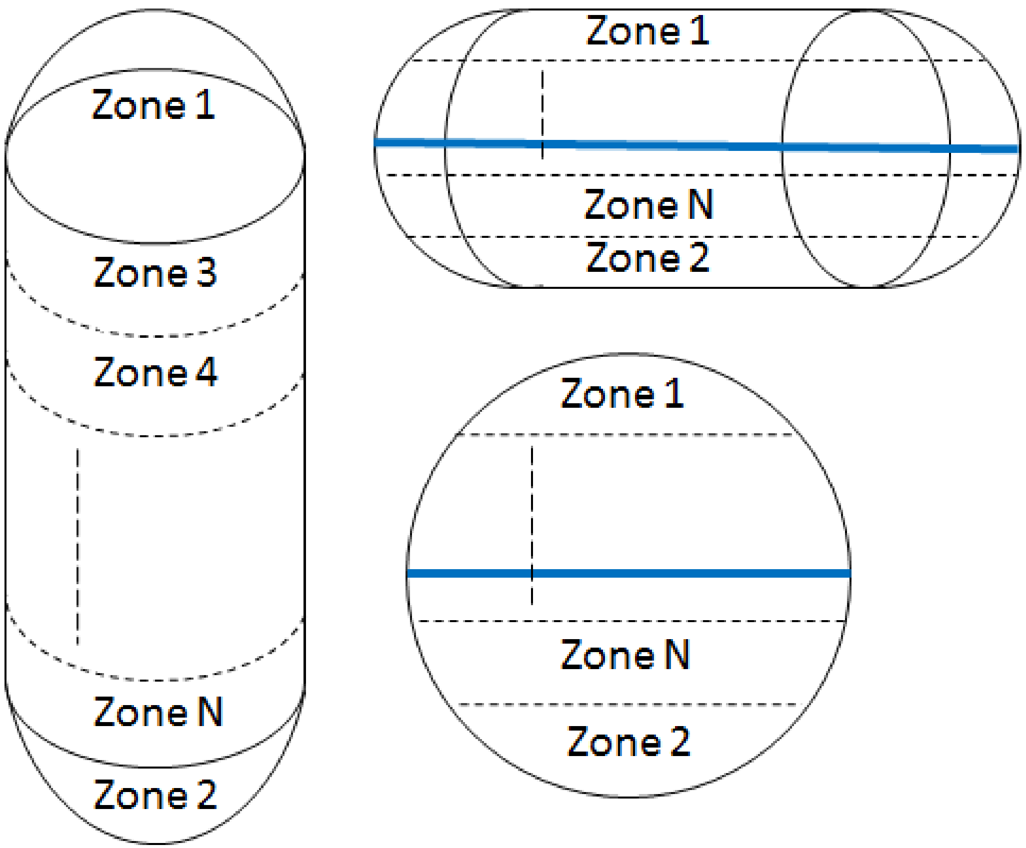
Source: Brooks, D. "Thermal Inbreathing Requirements of Low Pressure Storage Tanks at Elevated Temperatures" (2012)

# Heat transfer across the wall is modeled in detail for each wall segment in SuperChems™



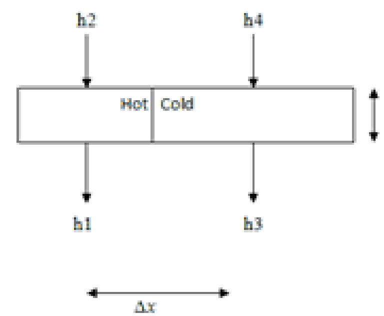

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# SuperChems™ segments vessels into multiple zones and accounts for heat conduction across the wall and between the zones using the effective conduction length method




$$\Delta x = (kt)^{1/2}\left[\frac{1}{(h_1+h_2)^{1/2}+(h_3+h_4)^{1/2}}\right]$$

where $t$ is the thickness of the solid layer in m, $h_1$ and $h_3$ are internal heat transfer coefficients leaving the solid layer in W/m$^2$ K, $h_2$ and $h_4$ are external heat transfer coefficients entering the solid layer in W/m$^2$ K.




Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# First, we will consider model predictions for non-condensable vapors

- Air

# The following data set was published by Sigel - “Practical And Theoretical Study Of The Ventilation Of Fixed Roof Tanks” Experimental)

- Tank was empty (i.e. dry air)
- Tank capacity = 600 m$^3$
- Experiment done in Germany on 29 July 1980

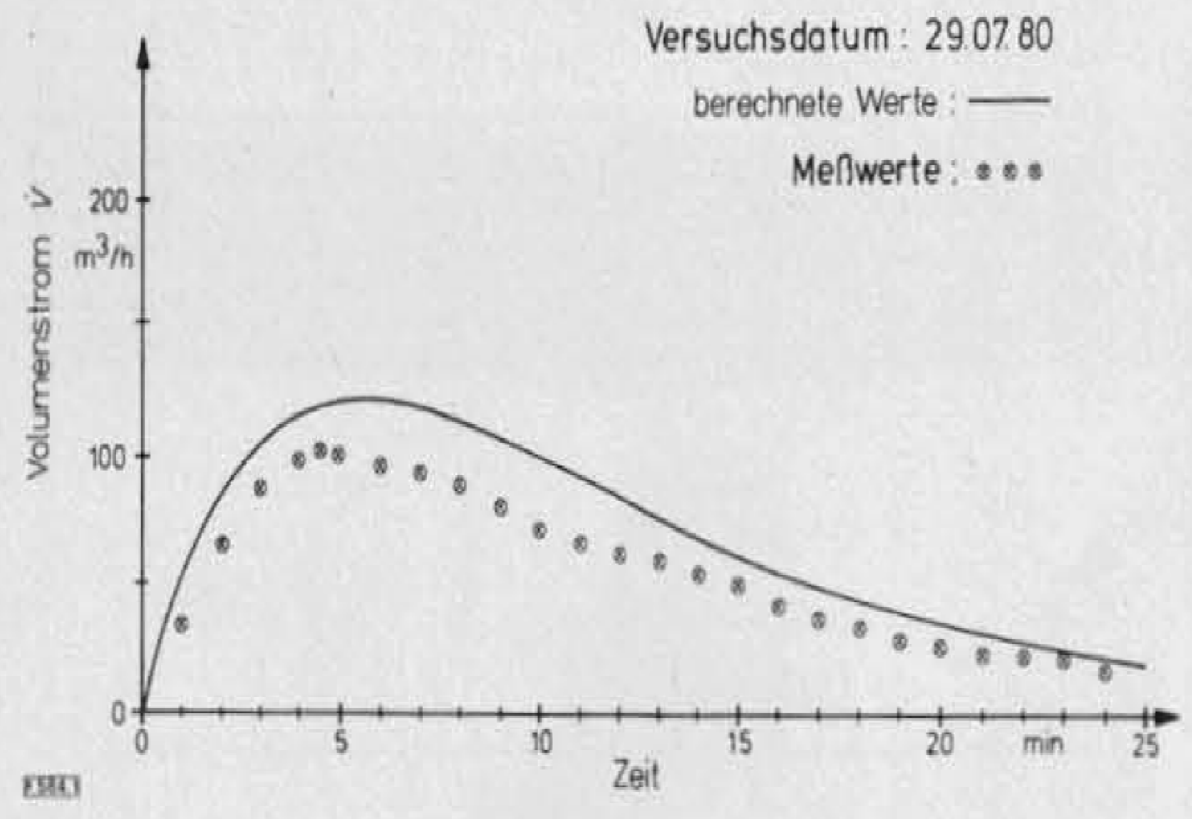


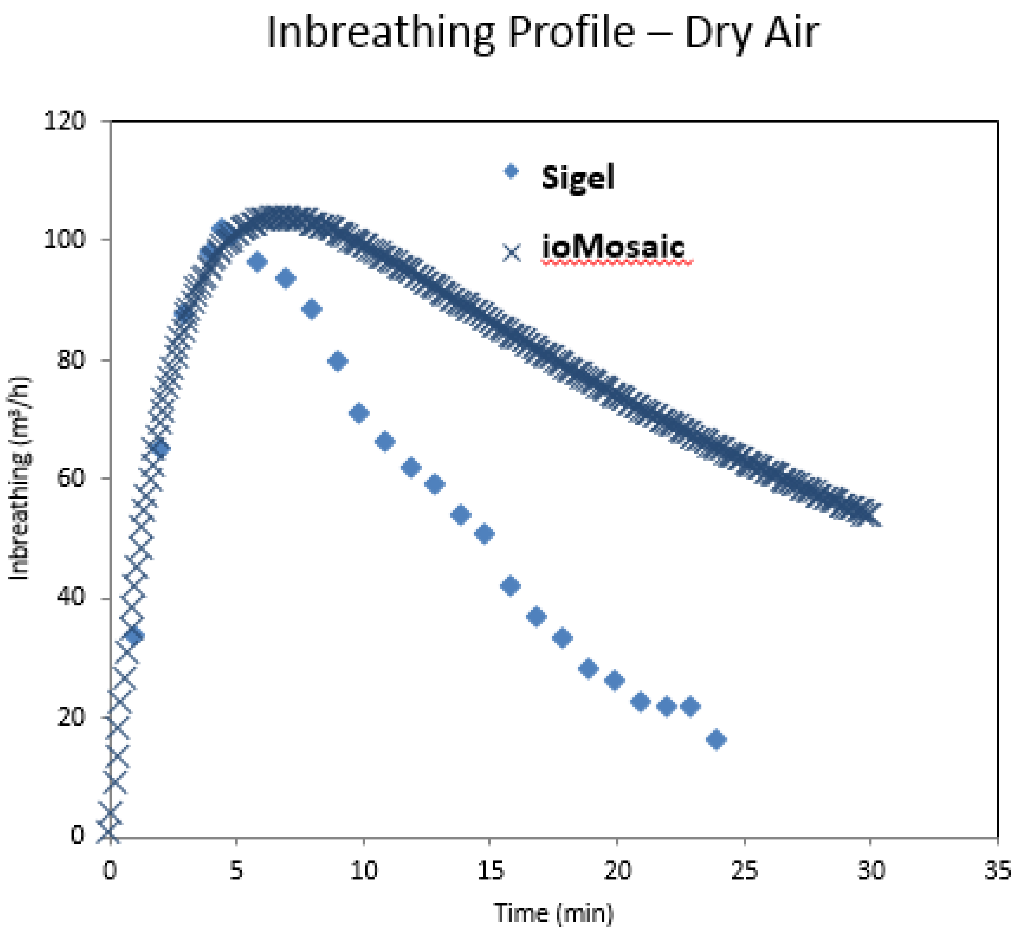

Abb. 1. Der Volumenstrom als Funktion der Zeit.

Source: Sigel, R., Kuxdorf, B., Meiss, R. and Schwarz, H. “Praktische und theoretische Untersuchung der Beatmung von Festdachtanks“ (1983)

# We simulated Siegel's experiment using the following parameters (best estimates)

- Vessel: H = 10.6 m; D = 8.5 m; s = 5 mm (wall thickness)
- Mixture: 79 mol% Nitrogen; 21 mol% Oxygen
- Ambient Temperature = 25° C
- Cloud Coverage = 0%
- Average Wind Speed = 2 m/s
- Location: Berlin, Germany (Longitude: 13.417 degrees  Latitude: 52.5 degrees)
- Tank is exposed to solar heating

# Model predictions are reasonable considering some uncertainty in some parameter values not reported by the experiments




| Parameters | SuperChems™ |
|---|---|
| $H_{gas}$ | 5.56 W/m²K |
| $H_{rain}$ | 16.26 W/m²K |
| $m_{rain}$ | 12 kg/m²h |

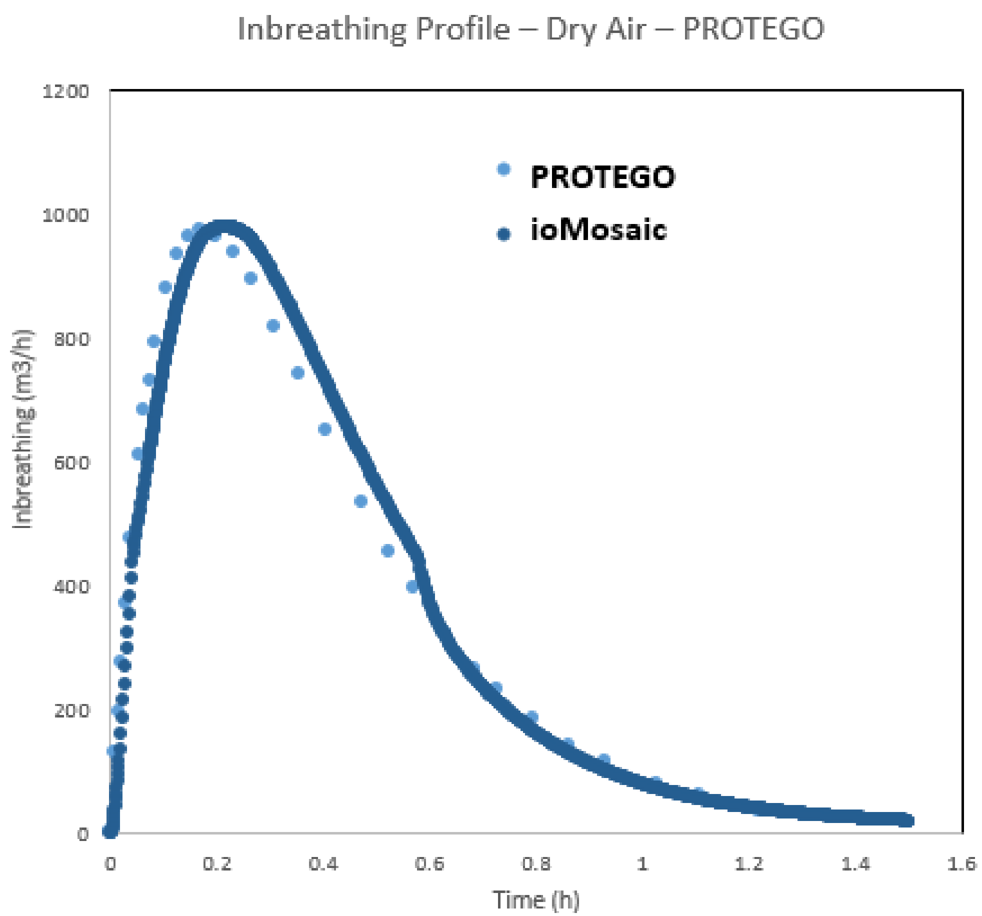
$\Delta P_{max}$ = -0.01 psig

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# Next we reproduce Protego's simulations

- Ambient Temperature = 15° C
- Cloud Coverage = 100%
- Average Wind Speed = 5 m/s
- Tank is NOT exposed to solar heating
- Vessel: H = 12 m; D = 20 m; s = 5 mm; V = 3980 $m^3$ (single volume)
- Mixture: 79 mol% Nitrogen; 21 mol% Oxygen

# Very good agreement is obtained for inbreathing requirements



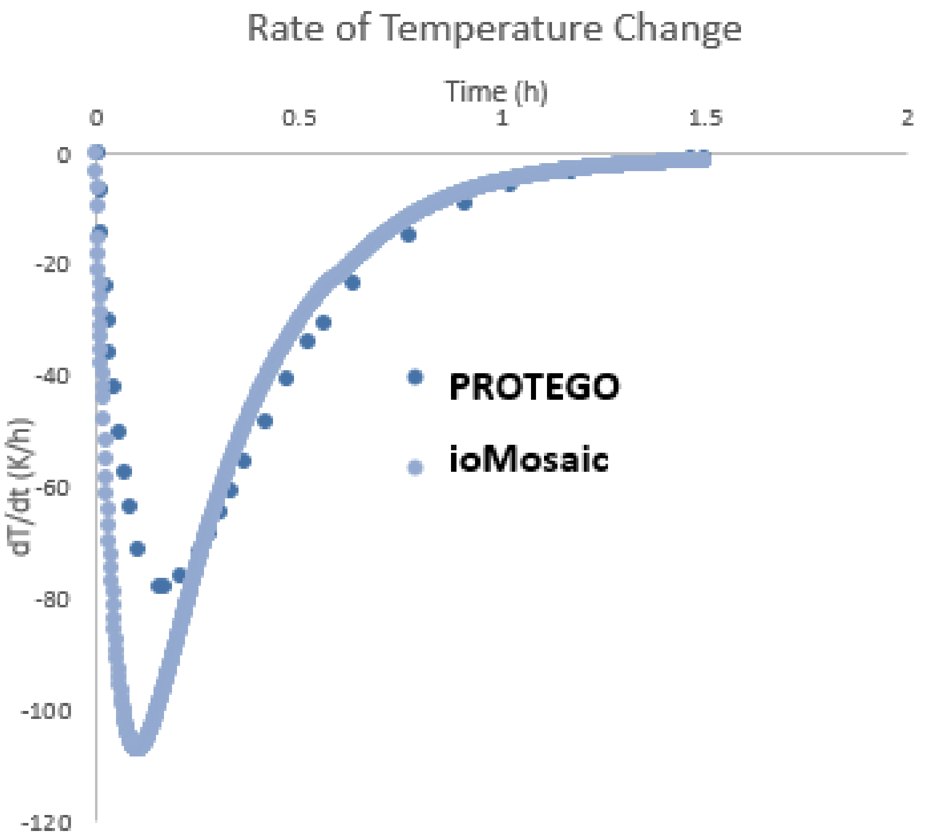

| W/m²K | PROTEGO | ioMosaic |
|---|---|---|
| $H_{gas}$ | 5 | 5 |
| $H_{rain}$ | 37 | 37.255 |

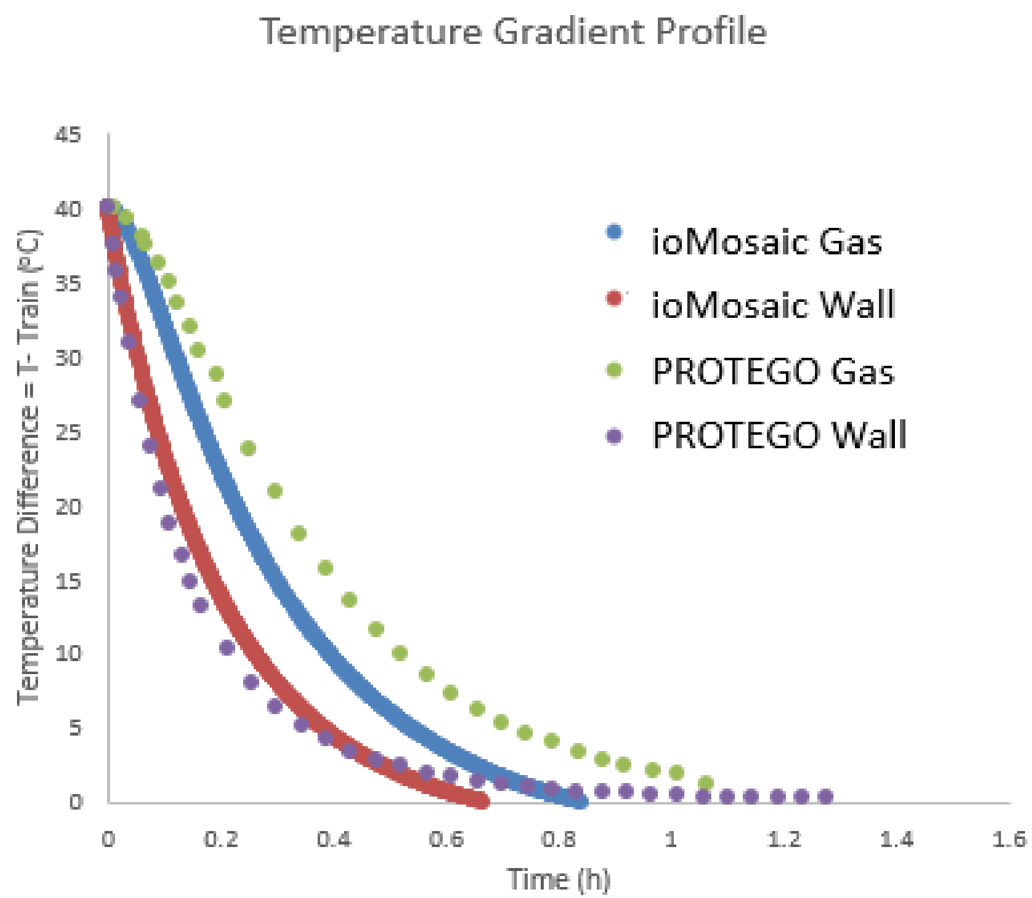
| | Hole Size | ΔP |
|---|---|---|
| ΔP | 3.16” | -0.26 psig |

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# Protego's tank (Dry Air) – 3.16" hole

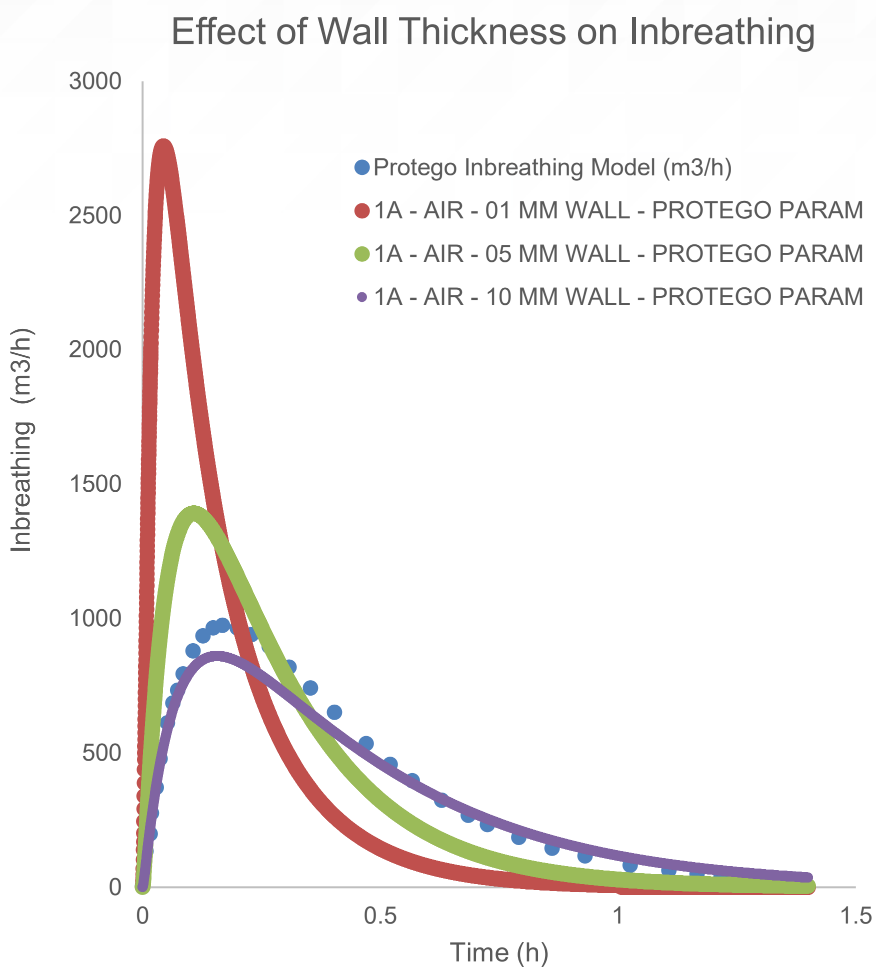
| | PROTEGO | ioMosaic |
|---|---|---|
| Minimum dT/dt (K/h) | -78.3 | -107.10 |



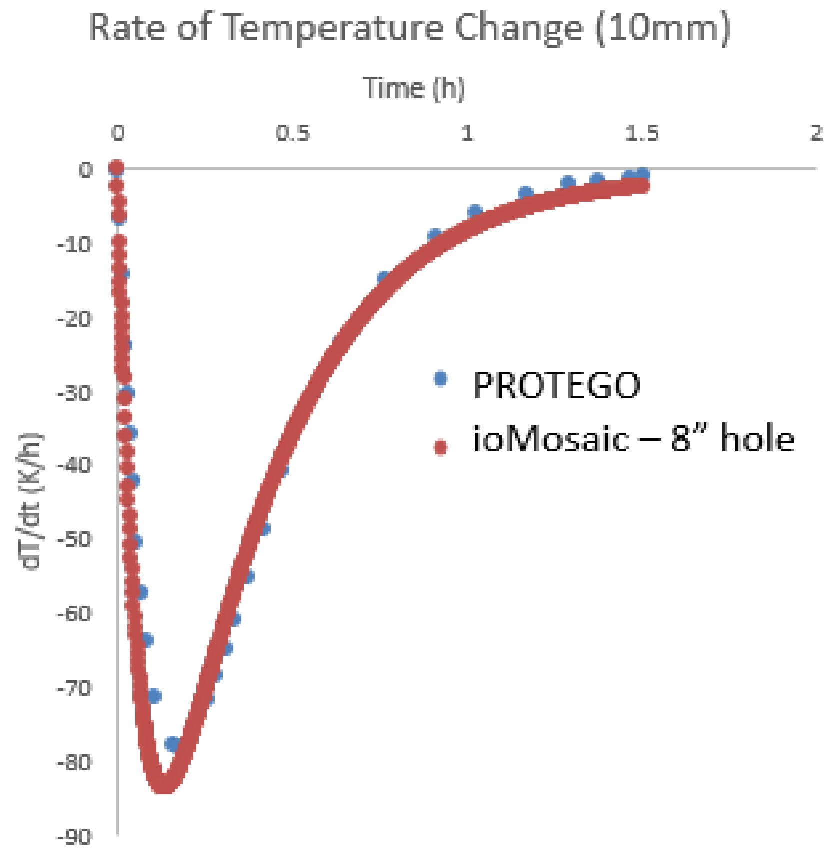

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

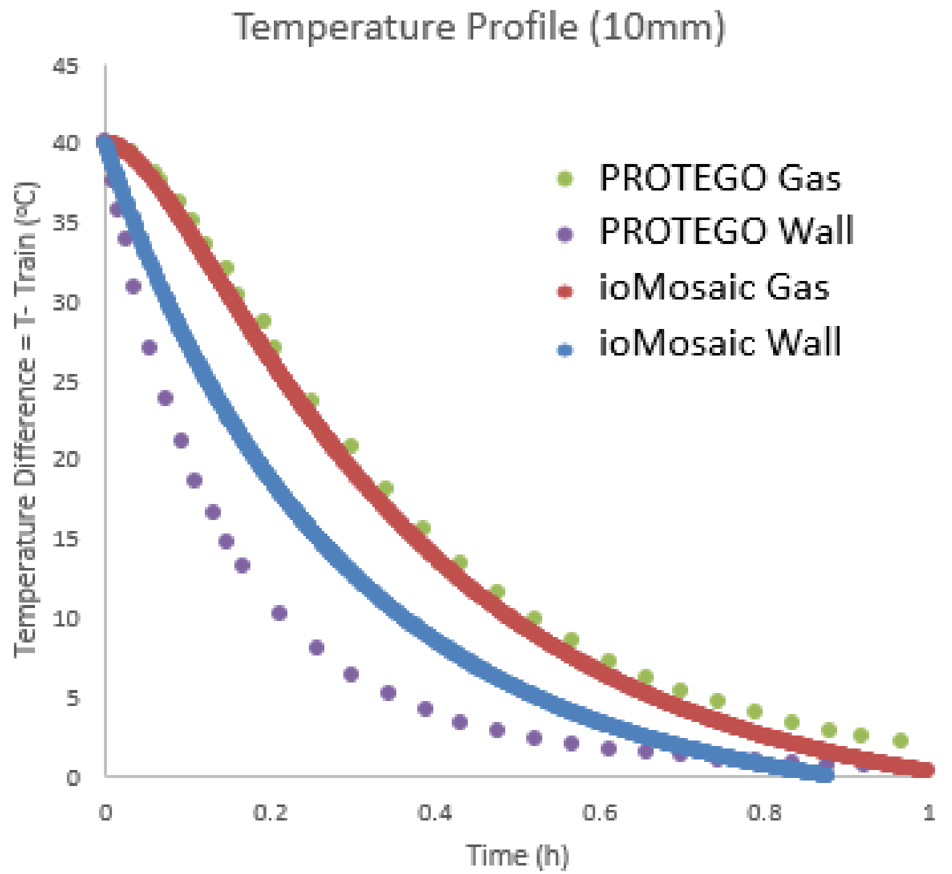
# Increasing the shell wall thickness reduces the maximum inbreathing $V_{max}$ BUT yields accurate temperature profiles




Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# Protego's tank – 10 mm Wall Thickness




| | PROTEGO | ioMosaic (10mm) |
|---|---|---|
| Minimum dT/dt (K/h) | -78.3 | -85.8 |

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation



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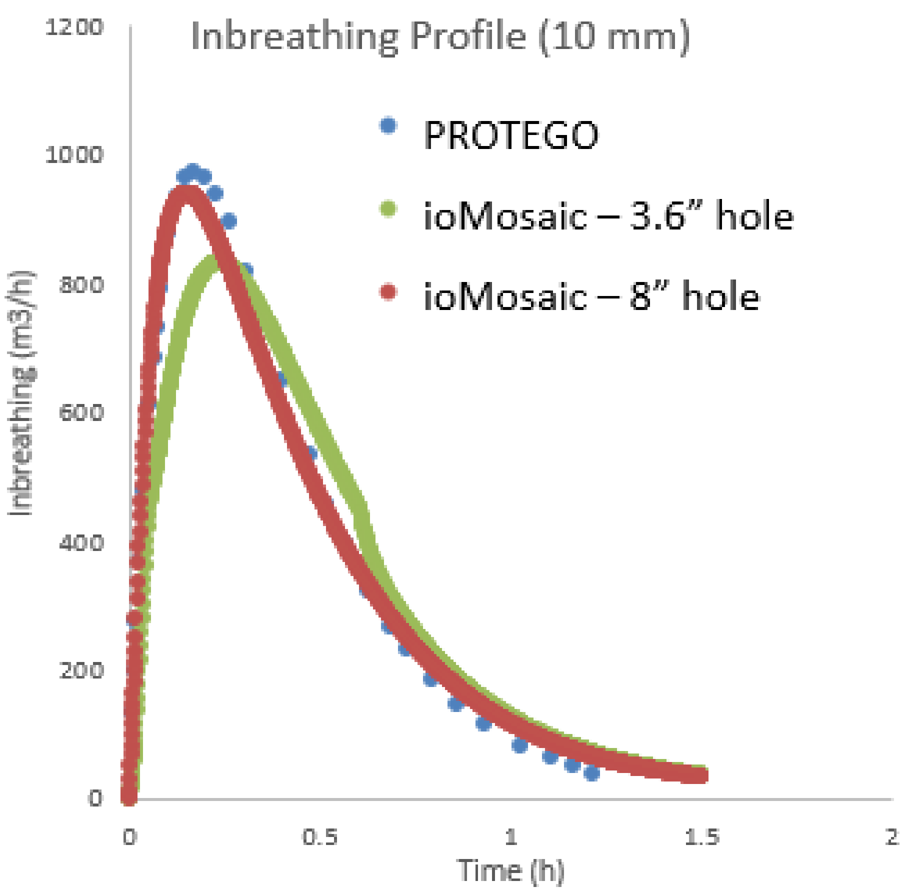
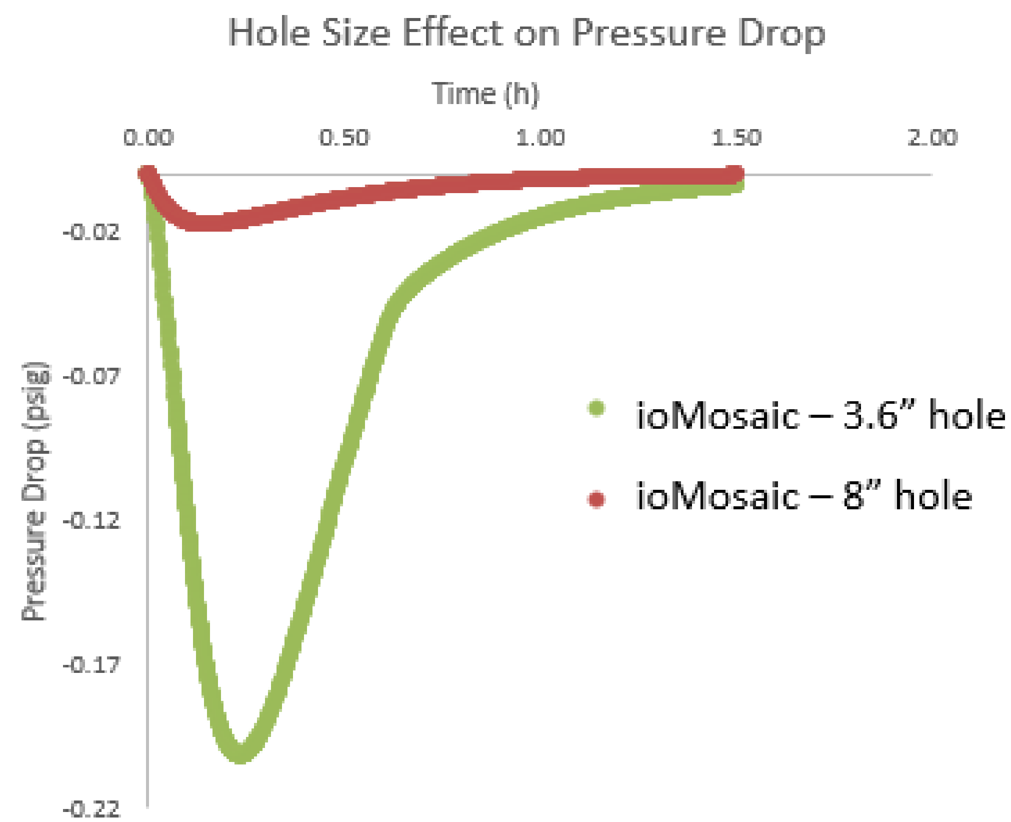
# Protego's tank – 10 mm Wall Thickness




| W/m²K | PROTEGO | ioMosaic |
|---|---|---|
| $H_{gas}$ | 5 | 5 |
| $H_{rain}$ | 37 | 37.255 |

| Hole Size | ΔP |
|---|---|
| 8" | -0.02 psig |

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# Next, we will consider model predictions for condensable vapors

- Protego used a vapor only vessel when they carried out the inbreathing simulation
- Not suitable since the tank cannot contain pure water vapor at 55° C and 1 atm. Water exists as a two-phase mixture with air
- We used SuperChems™ two-phase vessel and wall dynamics
- Initial liquid level of water: ILL = 0.15 %
- Purged the tank with Nitrogen gas to get water to saturation condition at 55° C and 1 atm

# We estimated the free convection heat transfer coefficient ($h_{gas}$) corresponding to different values of wall thickness

- Protego's model assumed that the wall thermal capacity is negligible i.e. the wall thickness is very small (close to null)
- The mass of the stored gas in the tank is small compared to the mass of the steel shell
- The metal shell can keep the stored gas and walls warmer
- Reducing the shell thickness increases the conservativeness of the thermal inbreathing requirement
- We fixed the rain intensity ($h_{rain}$) & wall thickness (s=1mm; s=5mm; s=10mm) and varied $h_{gas}$ to match the inbreathing profiles reported by Protego

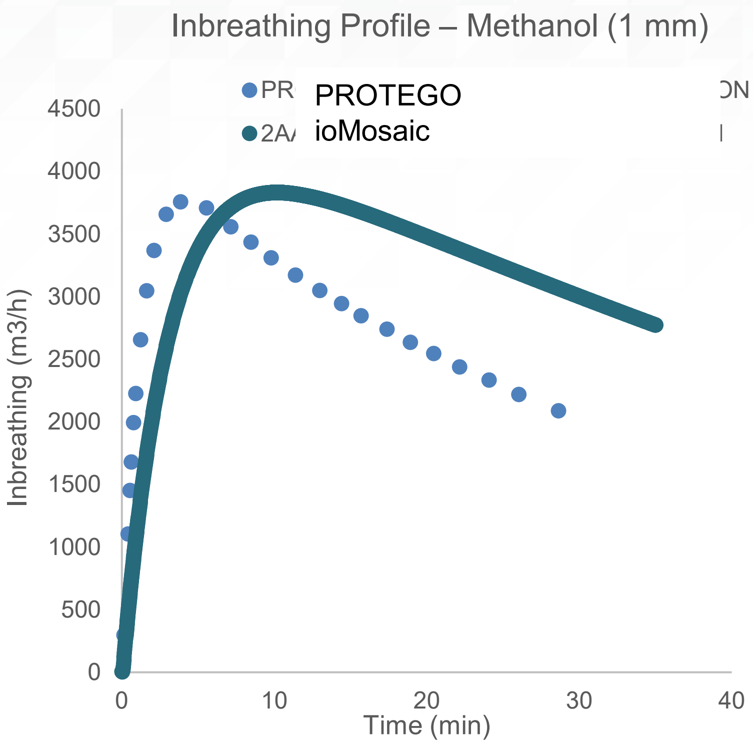
# We used the following parameter is these simulations

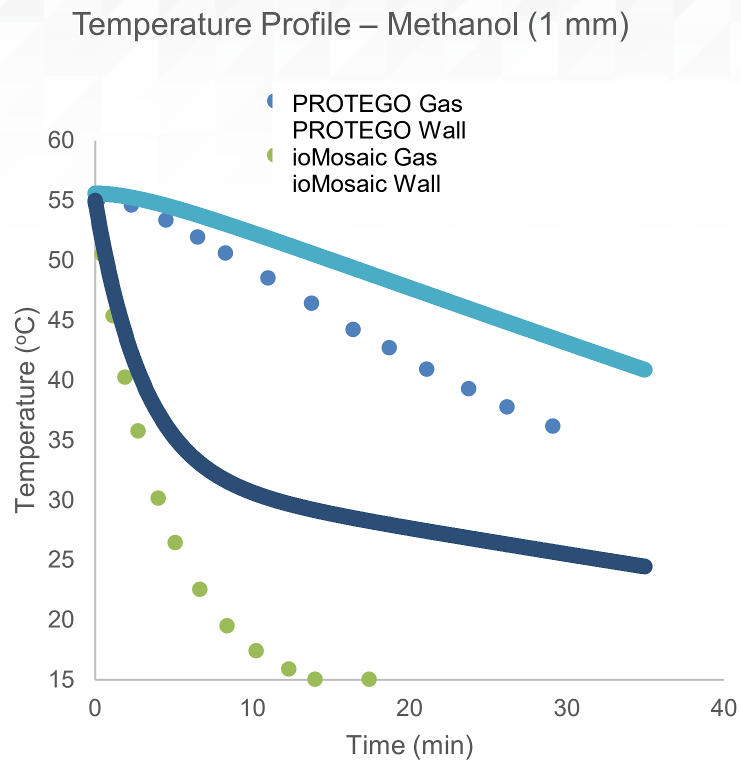
- Ambient Temperature = 15° C
- Tank is NOT exposed to solar heating
- Vessel: H = D = 20 m; s = [1, 5, 10] mm; V = 62,830 $m^3$
- Initial Liquid Level = 0.1%
- Fixed Heat Transfer Coefficients - Gas/wall = 5 $W/m^2K$, and Rain/wall = 50 $W/m^2K$

# The Protego model does not consider VLE while SuperChems™ does

- Vapors covered by decreasing volatility
  - Methanol > Ethanol > Heptane > Water > Decane
- Twophase model with 0.15% ILL
- Purge with nitrogen to achieve saturation
- Calculated profiles will not match Protego's predictions since we're accounting for the vapor-liquid equilibrium and they are not
- Target is to match the $V_{max}$ by varying $h_{gas}$

# Methanol simulations summary




| Input Parameters | |
|---|---|
| Hole size | 15” |
| $\Delta P_{max}$ | -0.022 psig |
| $H_{gas}$ | 35 W/m²K |
| $H_{rain}$ | 50 W/m²K |

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation



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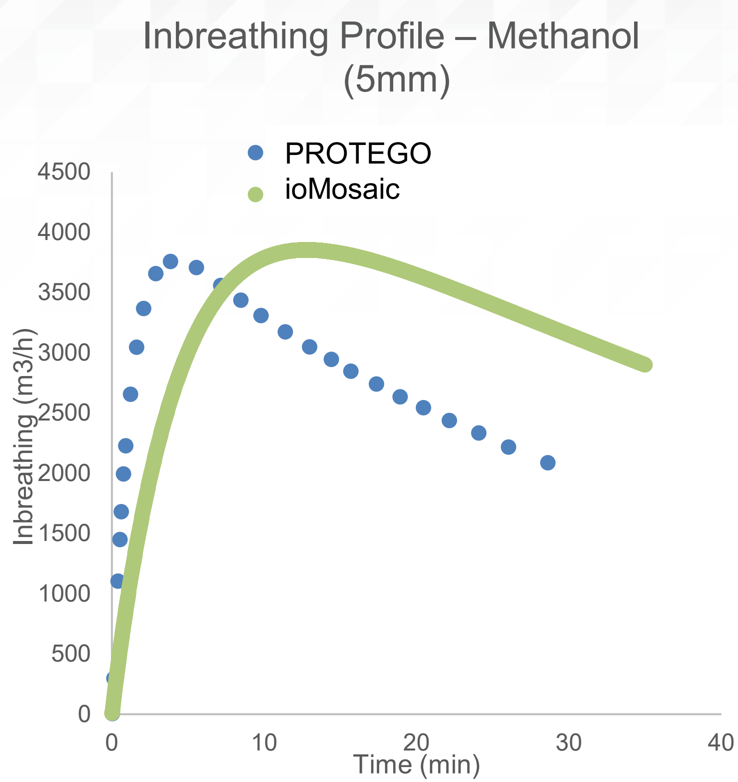
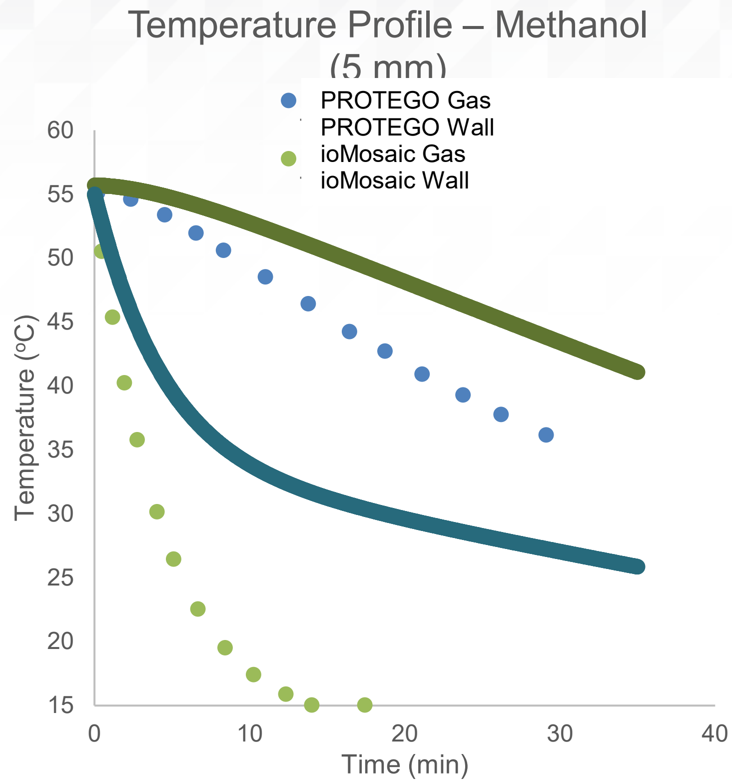
# Protego – Methanol – $H_{gas}$ for wall thickness = 5mm

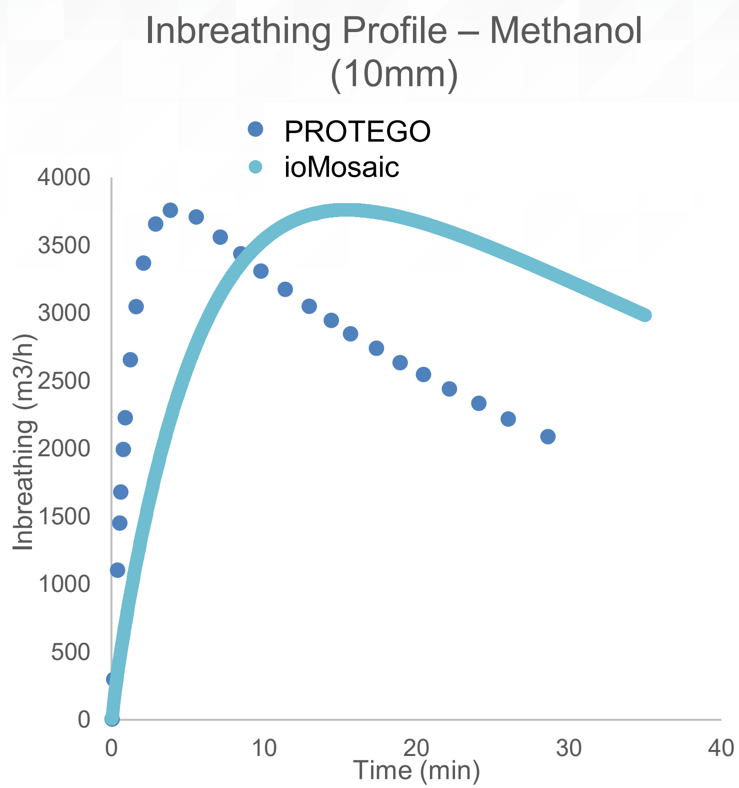


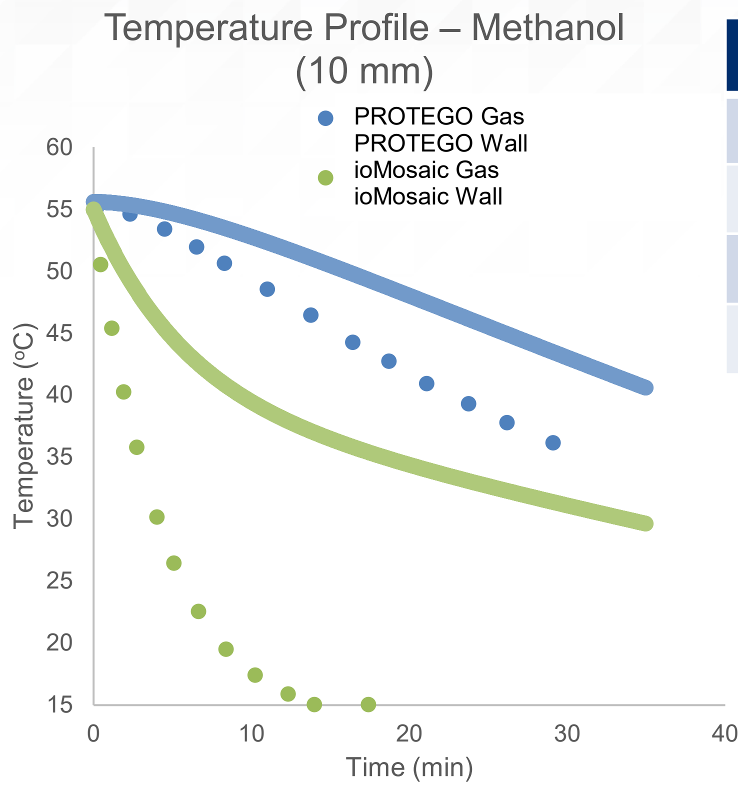




| Input Parameters | |
|---|---|
| Hole size | 15” |
| $\Delta P_{max}$ | -0.022 psig |
| $H_{gas}$ | **40** W/m²K |
| $H_{rain}$ | 50 W/m²K |

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# Protego – Methanol – $H_{gas}$ for wall thickness = 10mm

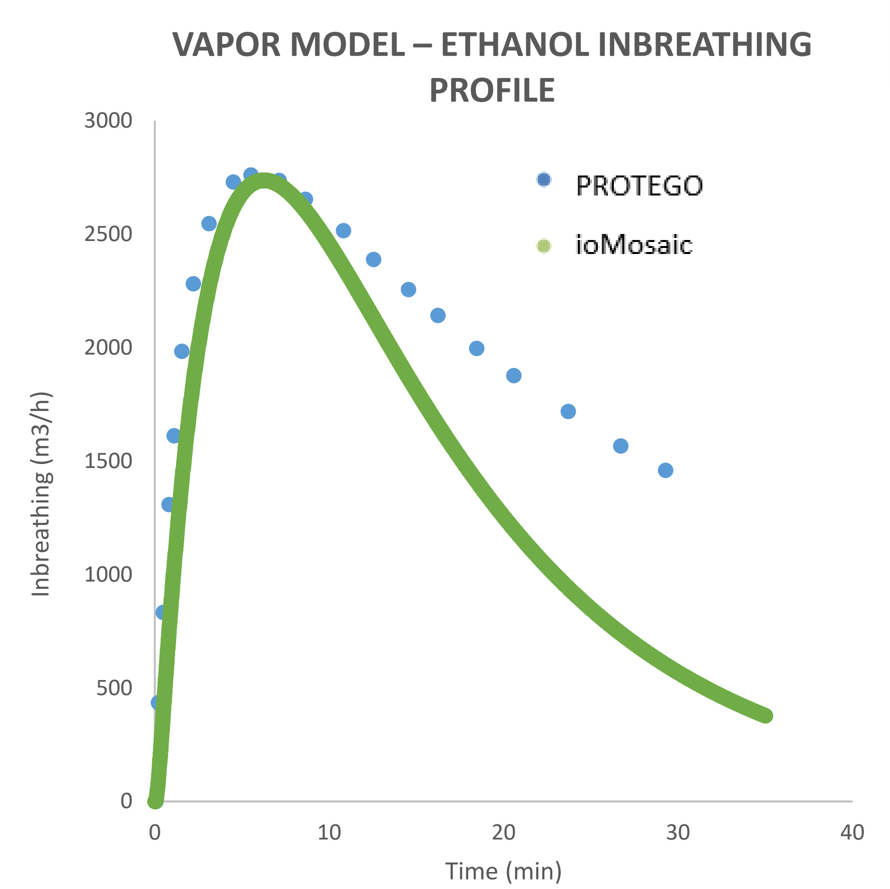



| Input Parameters | |
|---|---|
| Hole size | 15” |
| $\Delta P_{max}$ | -0.022 psig |
| $H_{gas}$ | **45** $W/m^2K$ |
| $H_{rain}$ | 50 $W/m^2K$ |

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# Protego uses Vapor Model – Replication using SuperChems™ Vapor Model

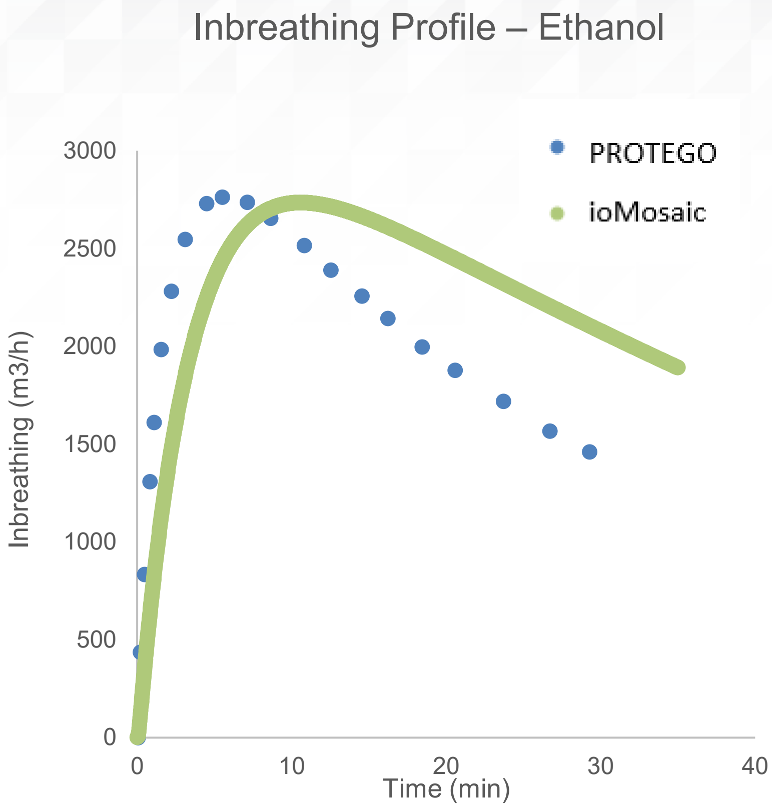


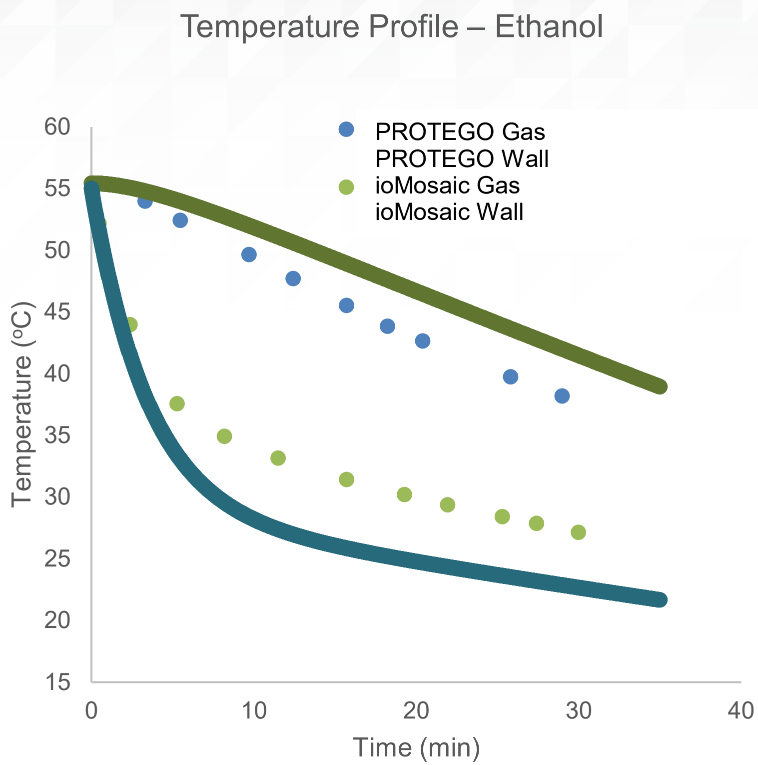

| | |
|---|---|
| $H_{gas}$ | 5 W/m²K |
| $H_{rain}$ | 50 W/m²K |

- Protego's data can be matched using our vapor model but fails in our 2-phase model
- Reason: Vapor model uses pure ethanol in the vapor state at 55° C and 0 psig
- On the other hand, N2 was added to EtOH in the 2-Phase model to lower the saturated ethanol vapor to 55° C at 0 psig
- Molar composition used in 2-phase model: 62 mol% Ethanol and 0.38 mol% Nitrogen

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# Protego – Ethanol – Replication in SuperChems™




| Input Parameters | |
|---|---|
| Hole size | 15” (cz 10” pulled a vacuum of -0.035 psig) |
| $\Delta P_{max}$ | -0.018 psig |
| $H_{gas}$ | 25 W/m²K |
| $H_{rain}$ | 50 W/m²K |

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation



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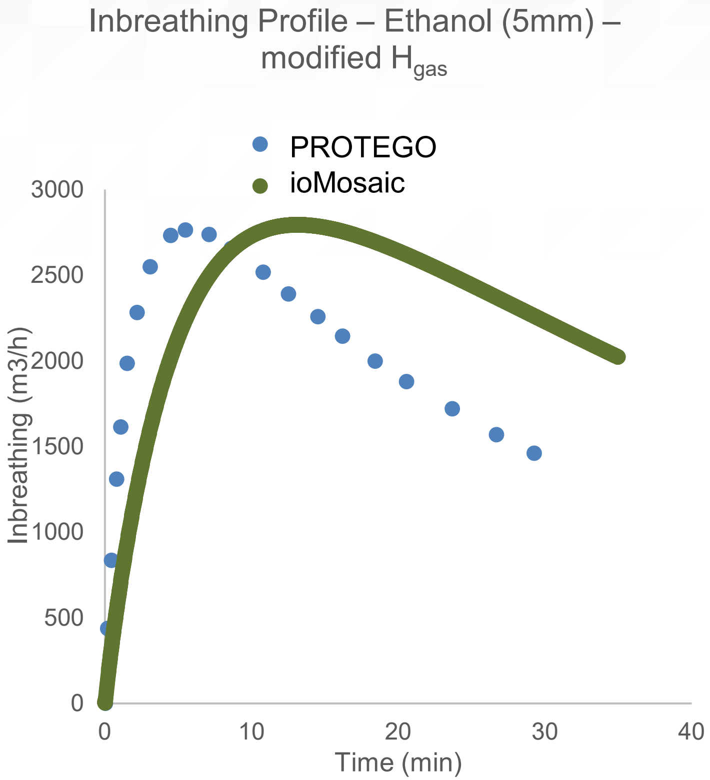
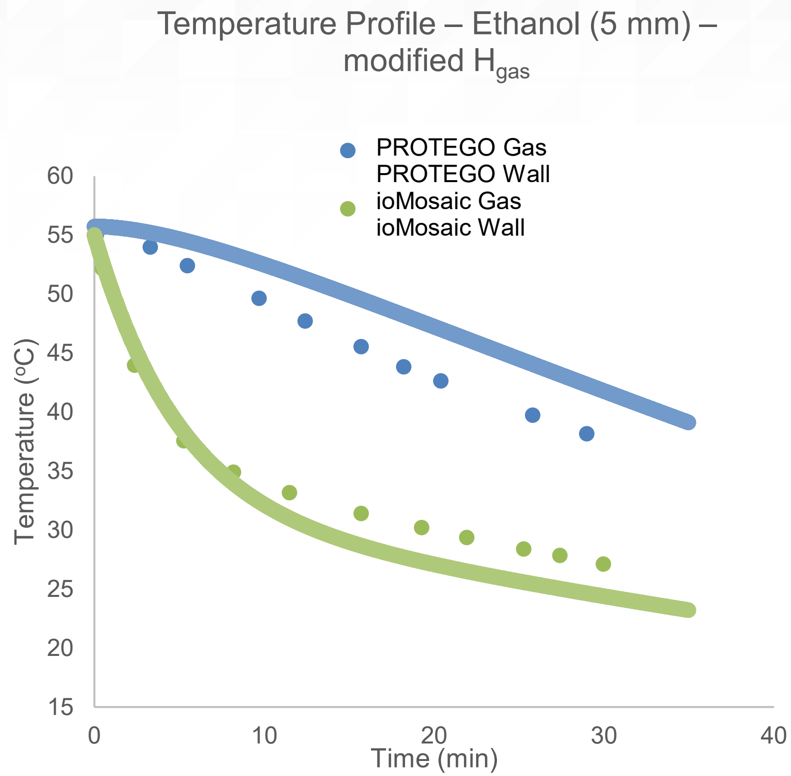
# Protego – Ethanol – $H_{gas}$ for wall thickness = 5mm



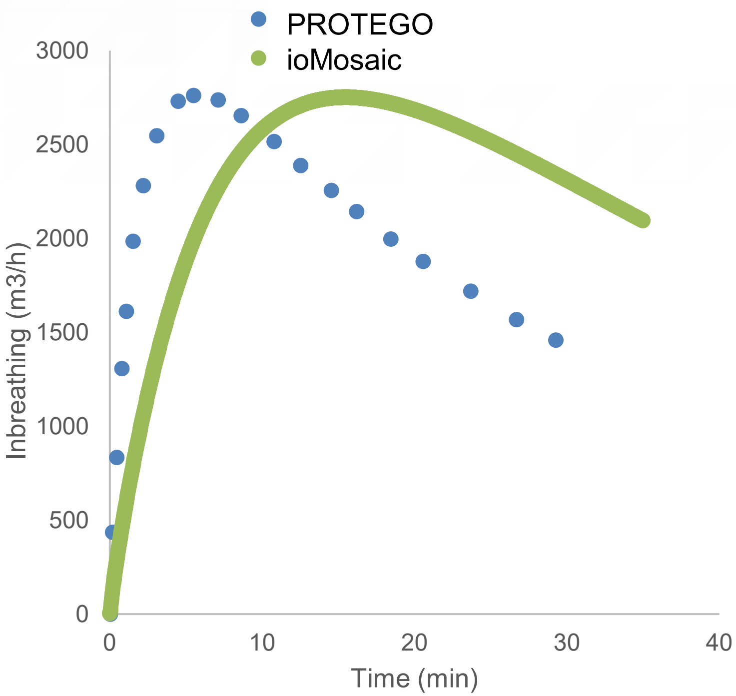




| Input Parameters | |
|---|---|
| Hole size | 15” |
| $\Delta P_{max}$ | -0.016 psig |
| $H_{gas}$ | **30** W/m²K |
| $H_{rain}$ | 50 W/m²K |

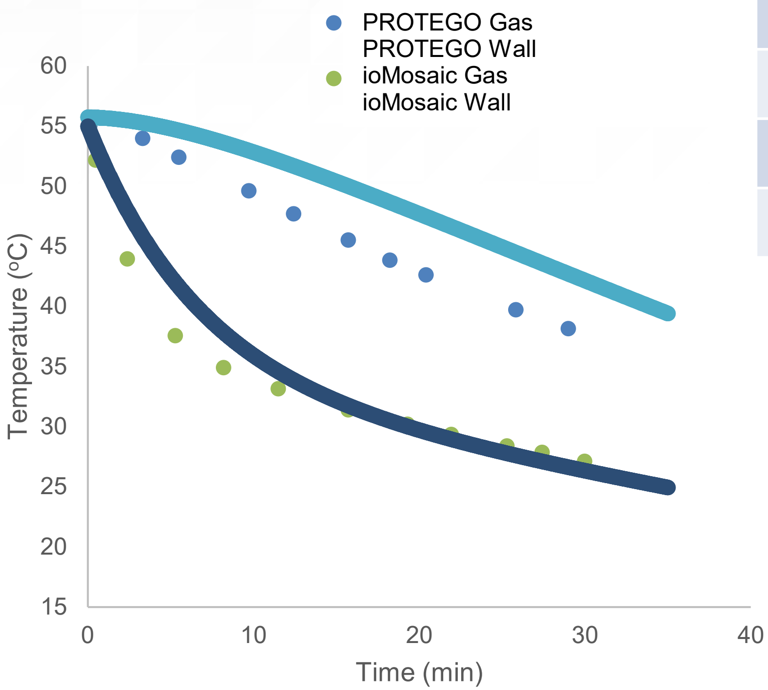
Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# Protego – Ethanol – $H_{gas}$ for wall thickness = 10 mm

Inbreathing Profile – Ethanol (10mm) – modified $H_{gas}$



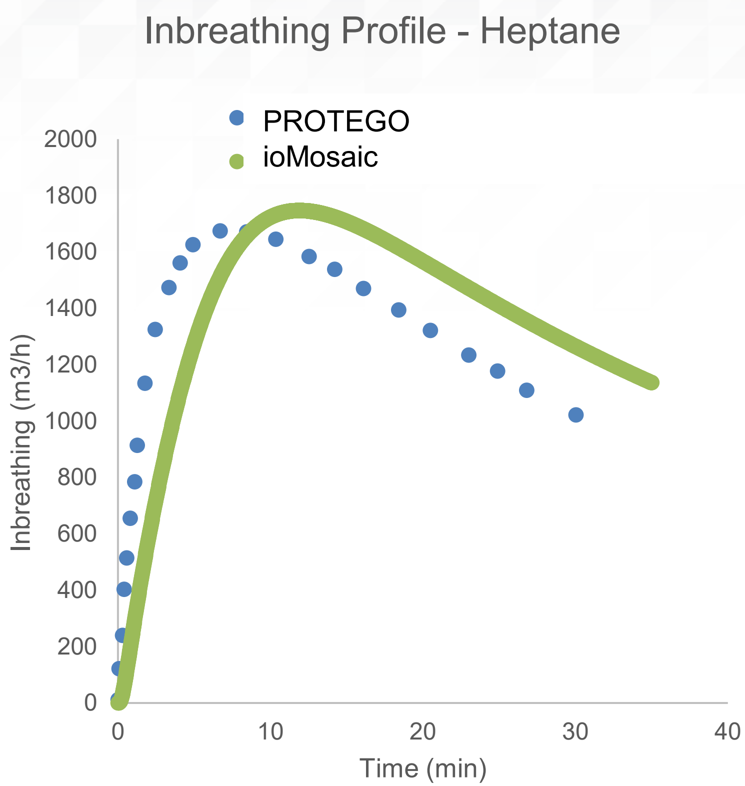

Temperature Profile – Ethanol (10 mm) – modified $H_{gas}$

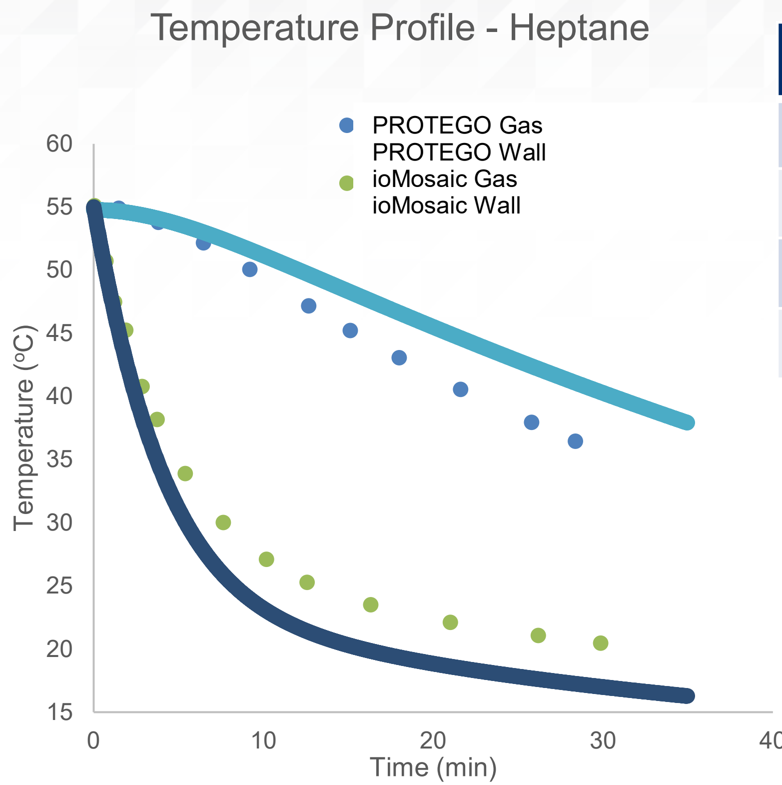



| Input Parameters | |
|---|---|
| Hole size | 15” |
| $\Delta P_{max}$ | -0.016 psig |
| $H_{gas}$ | **35** W/m²K |
| $H_{rain}$ | 50 W/m²K |

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# Protego – Heptane – Replication in SuperChems™

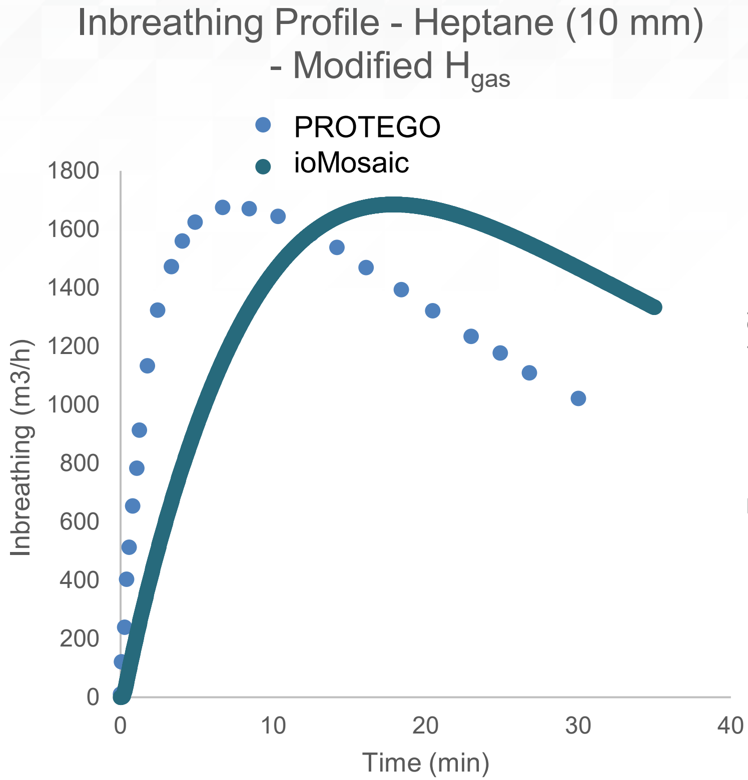


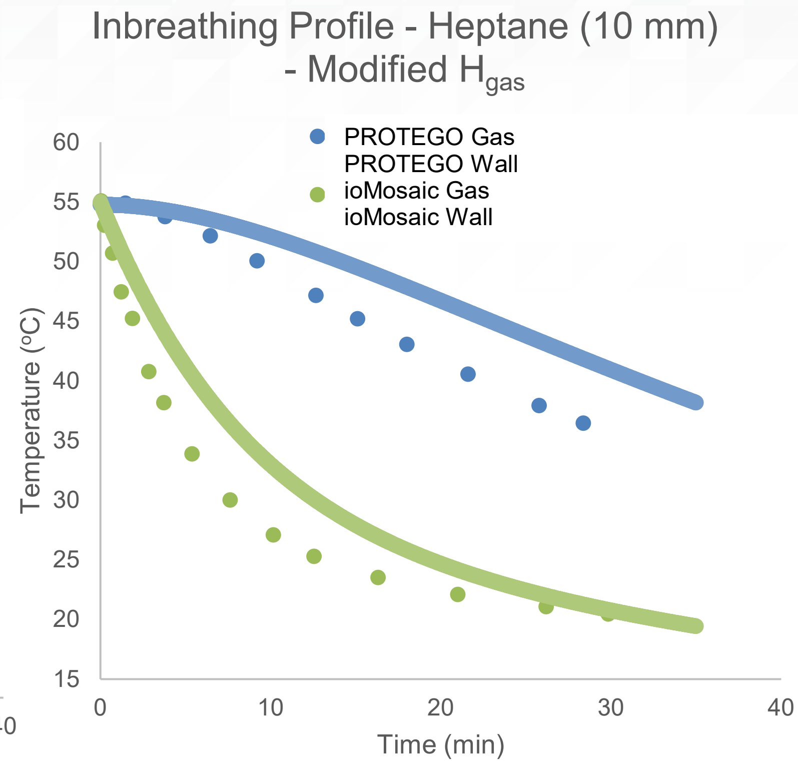




| Input Parameters | |
|---|---|
| Hole size | 10” |
| $\Delta P_{max}$ | -0.023 psig |
| $H_{gas}$ | 5 W/m²K |
| $H_{rain}$ | 50 W/m²K |

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# Protego – Heptane– $H_{gas}$ for wall thickness = 10mm

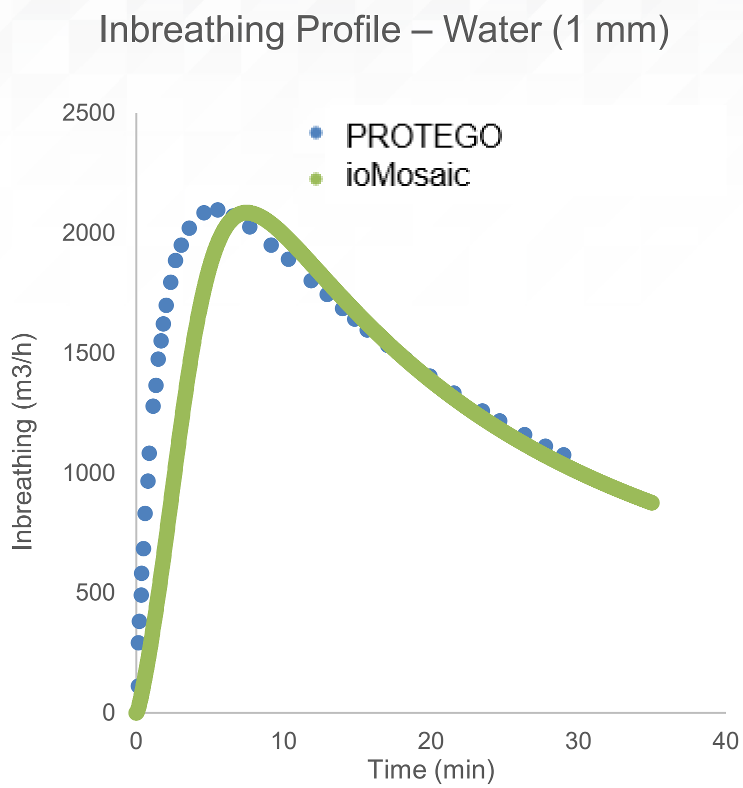


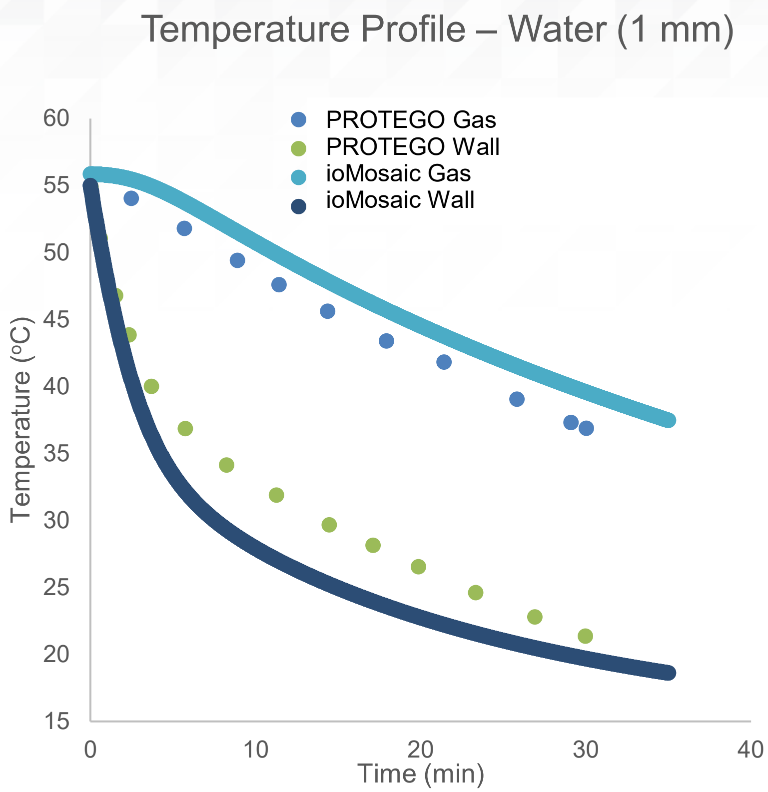




| Input Parameters | |
| --- | --- |
| Hole size | 15” |
| $\Delta P_{max}$ | -0.01 psig |
| $H_{gas}$ | **10** W/m²K |
| $H_{rain}$ | 50 W/m²K |

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# Protego – Water – Replication in SuperChems™



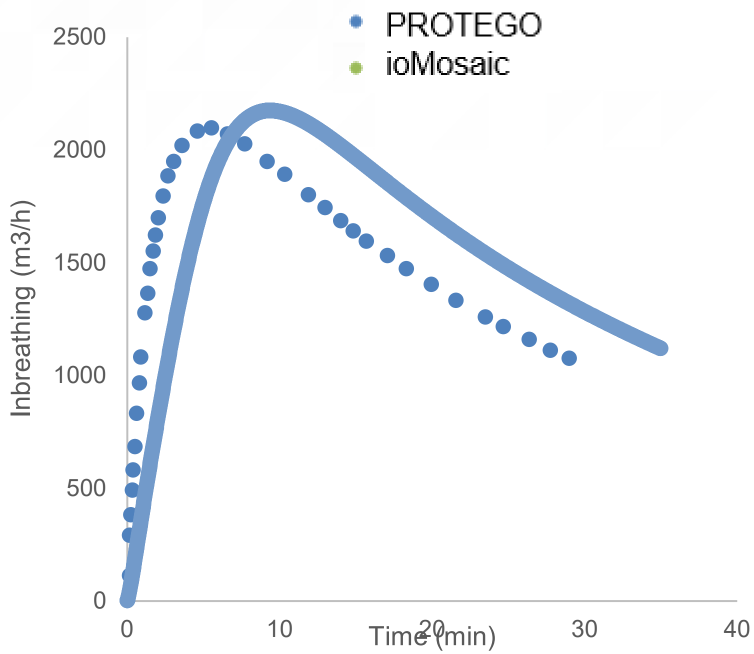




| Input Parameters | |
|---|---|
| Hole size | 10” |
| $\Delta P_{max}$ | -0.026 psig |
| $H_{gas}$ | 5 W/m²K |
| $H_{rain}$ | 50 W/m²K |

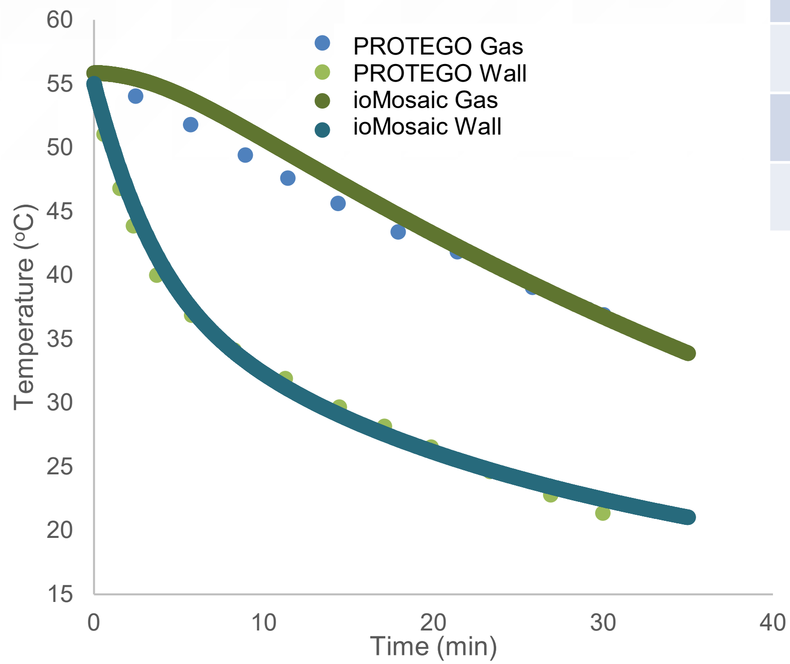
Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# Protego – Water – $H_{gas}$ for wall thickness = 5mm

Inbreathing Profile – Water (5mm) – modified $H_{gas}$




Temperature Profile – Water (5mm) – modified $H_{gas}$

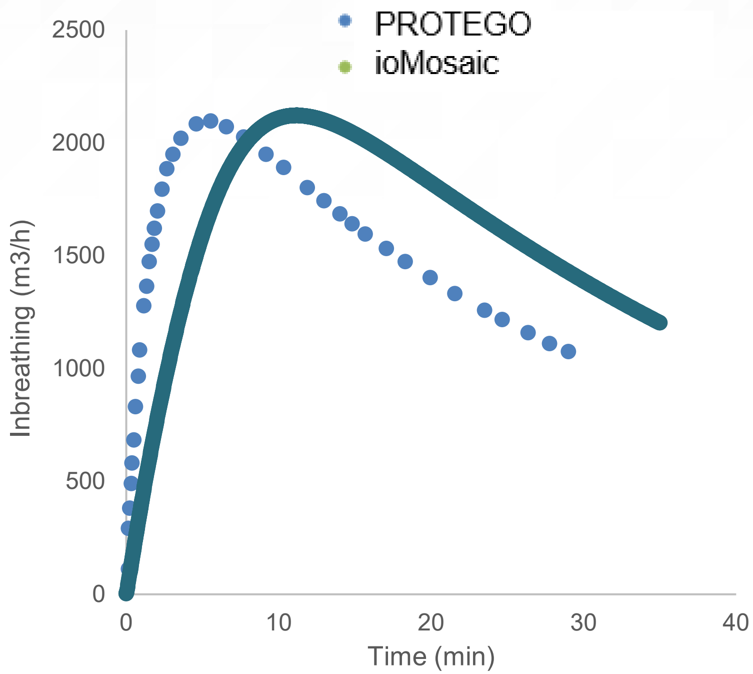



| Input Parameters | |
|---|---|
| Hole size | 10” |
| $\Delta P_{max}$ | -0.028 psig |
| $H_{gas}$ | **20** W/m²K |
| $H_{rain}$ | 50 W/m²K |

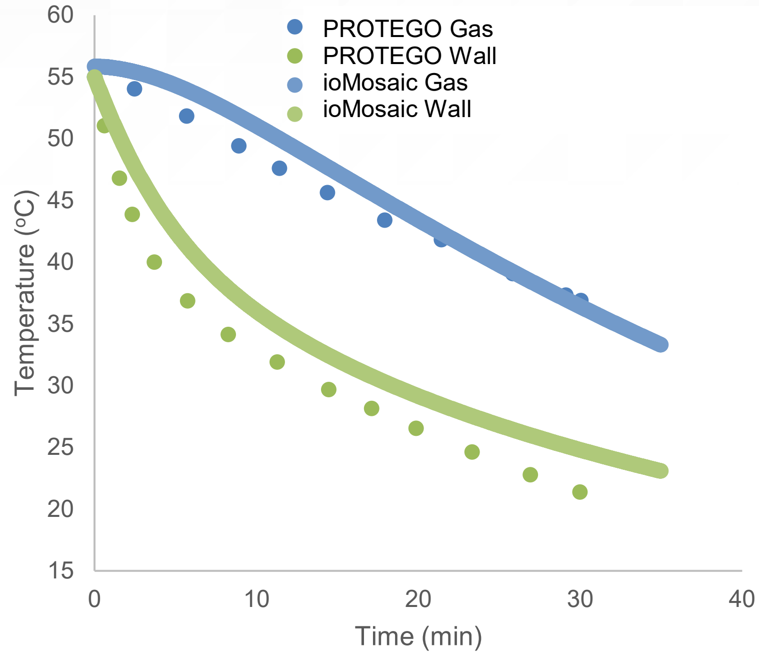
Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# Protego – Water – $H_{gas}$ for wall thickness = 10mm

Inbreathing Profile – Water (10mm) – modified $H_{gas}$



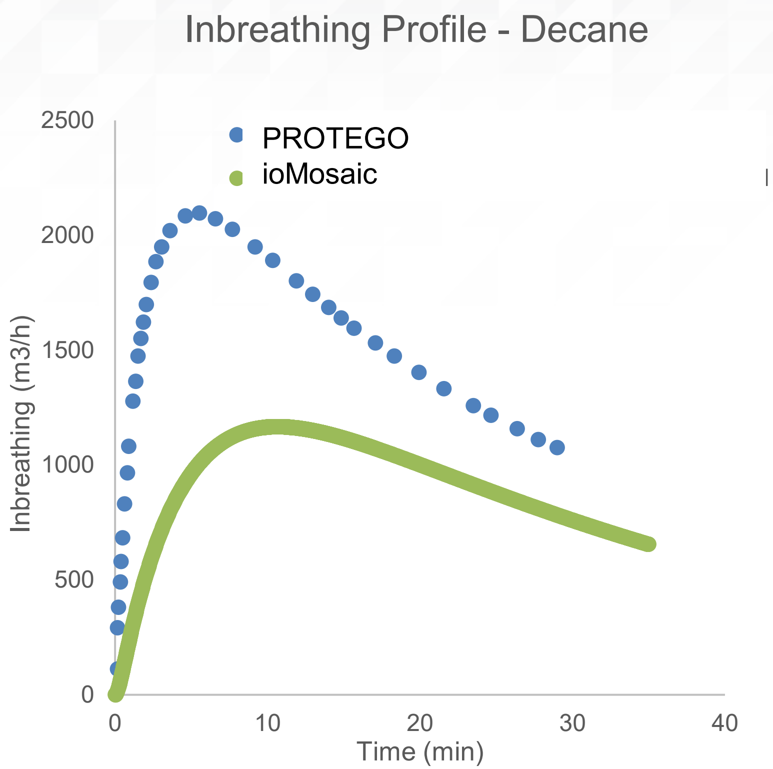

Temperature Profile – Water (10mm) – modified $H_{gas}$

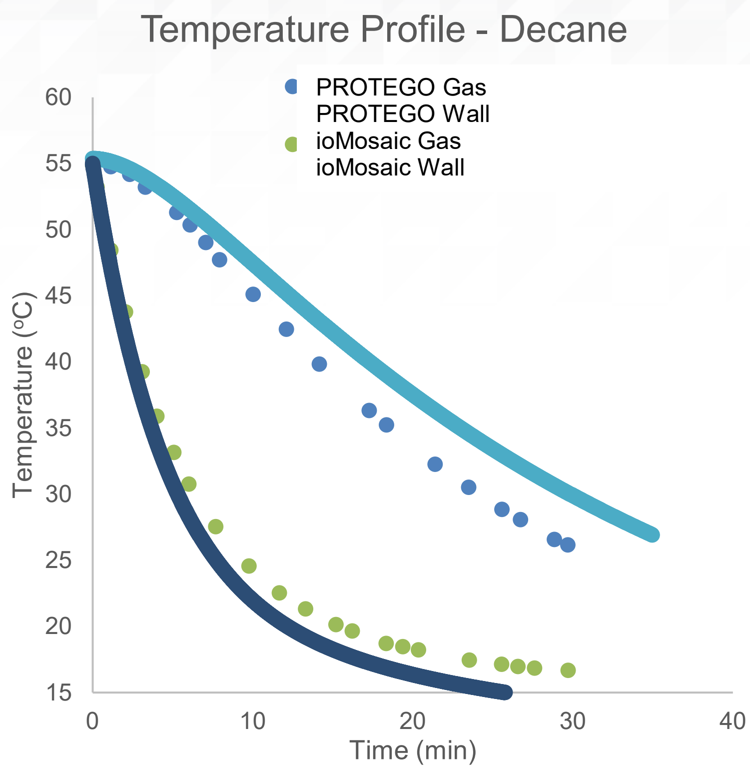



| Input Parameters | |
|---|---|
| Hole size | 10” |
| $\Delta P_{max}$ | -0.028 psig |
| $H_{gas}$ | **30** W/m²K |
| $H_{rain}$ | 50 W/m²K |

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# Protego – Decane – Replication in SC

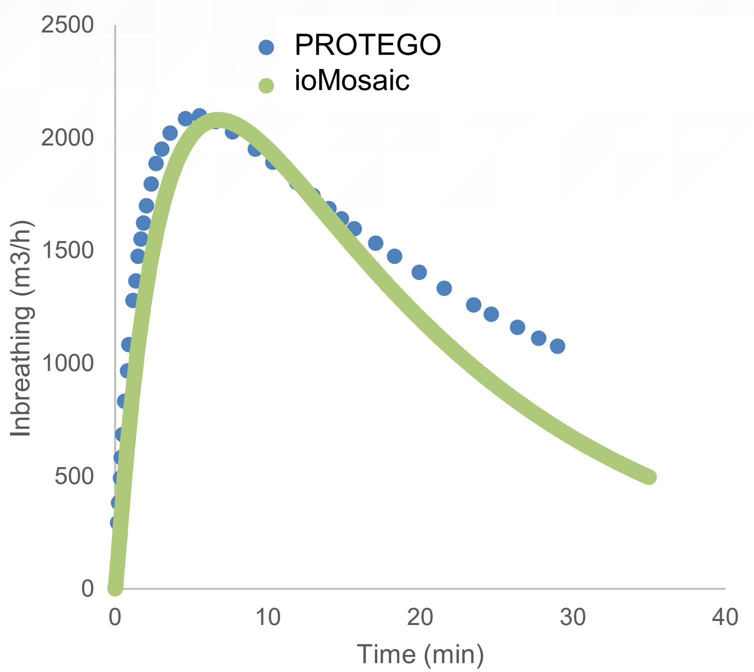


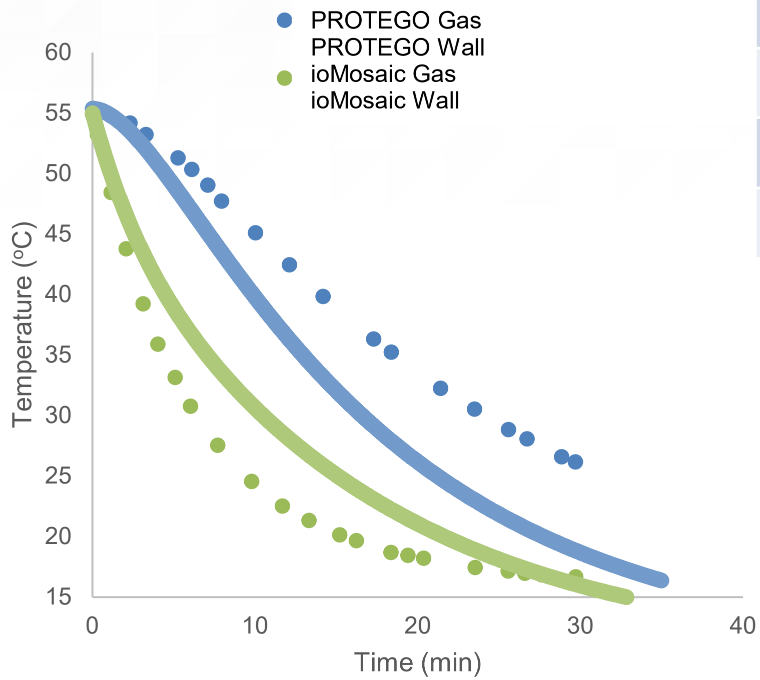




| Input Parameters | |
|---|---|
| Hole size | 10” |
| $\Delta P_{max}$ | -0.015 psig |
| $H_{gas}$ | 5 W/m²K |
| $H_{rain}$ | 50 W/m²K |

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# Protego – Decane – $H_{gas}$ for wall thickness = 5 mm




| Input Parameters | |
|---|---|
| Hole size | 15” |
| $\Delta P_{max}$ | -0.012 psig |
| $H_{gas}$ | **45** W/m²K |
| $H_{rain}$ | 50 W/m²K |

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation



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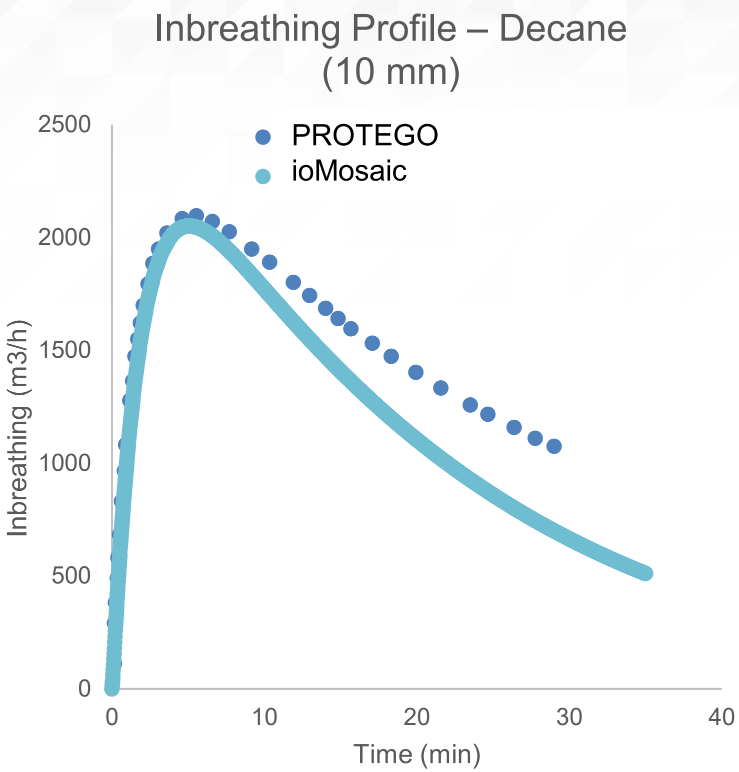
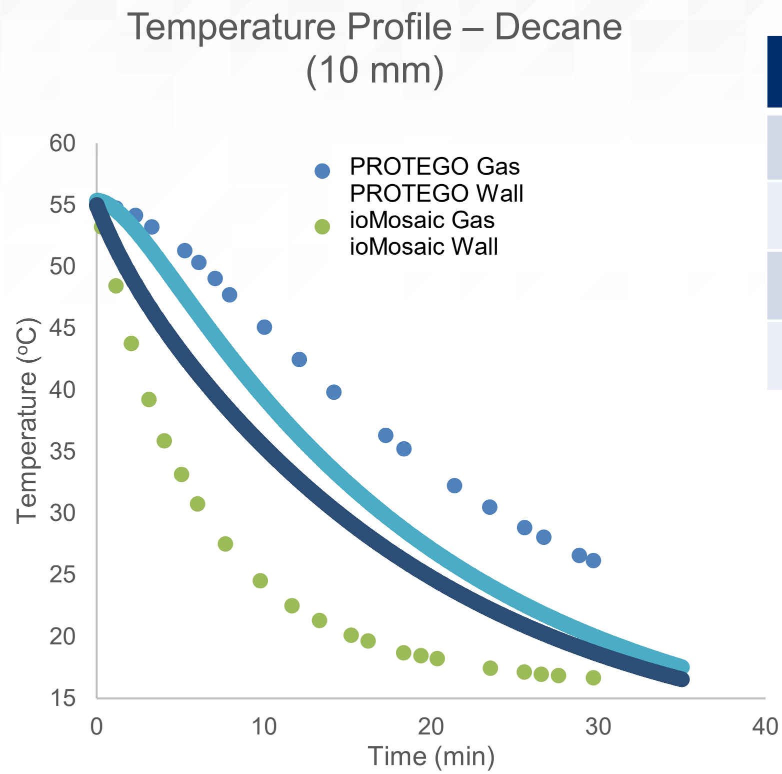
# Protego – Decane – $H_{gas}$ for wall thickness = 10 mm




| Input Parameters | |
|---|---|
| Hole size | 15” |
| $\Delta P_{max}$ | -0.012 psig |
| $H_{gas}$ | 100 W/m²K |
| $H_{rain}$ | 50 W/m²K |

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# Our detailed two-phase simulations show that the assumption of 5 $W/m^2/K$ is not adequate for condensable vapors

| $h_{gas}$ ($W/m^2K$) | 1 mm | 5 mm | 10 mm |
|---|---|---|---|
| Methanol | 35 | **40** | 45 |
| Ethanol | 25 | **30** | 35 |
| Heptane | 5 | **5** | 10 |
| Water | 5 | **20** | 30 |
| Decane | 5 | **45** | 100 |
| Air | 5 | N/A | 15 |

# API 2000 Thermal Inbreathing relief equation is adequate for dry air, water, heptane and decane vapors but underpredicts the relief requirement for both methanol and ethanol vapors

| Vapor | $V_{max,\ SC}$ ($Nm^3/h$) | $V_{max,\ API\ 2000}$ ($Nm^3/h$) | % Deviation (API-Model)/Model | API 2000 Suitable? (Y/N) |
|---|---|---|---|---|
| Methanol | 3818 | 2278 | - 40 | N |
| Ethanol | 2757 | 2278 | - 17 | N |
| Heptane | 1745 | 2278 | +31 | Y |
| Water | 2175 | 2278 | +5 | Y |
| Decane | 2079 | 2278 | +10 | Y |
| Air | 940 | 1655 | +76 | Y |

Source: API 2000 - API equation parameters used: C = 5, Ri = 1, $\dot{V}_{IT} = 5\, V_{tk}^{0.7}$

# These findings are supported by large scale test data

# Holtkoetter (1997) - Effect of Condensation on Thermal Inbreathing (Experimental)

- Tested 3 different vapors: methanol, isopropanol, and water
- Differentiated between vapor condensation happening (1) at the wall and (2) in the bulk (forms an aerosol)
- Tank capacity = 1.18 $m^3$

Abbildung 1.
Schema der Versuchsanlage.

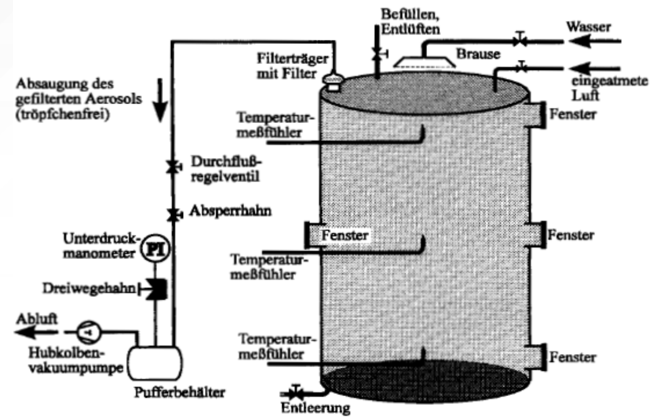
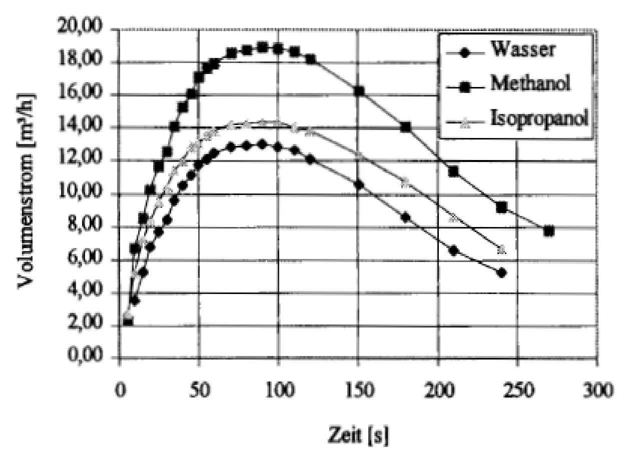



Abbildung 2.
Atmungsverhalten verschiedener Flüssigkeiten.

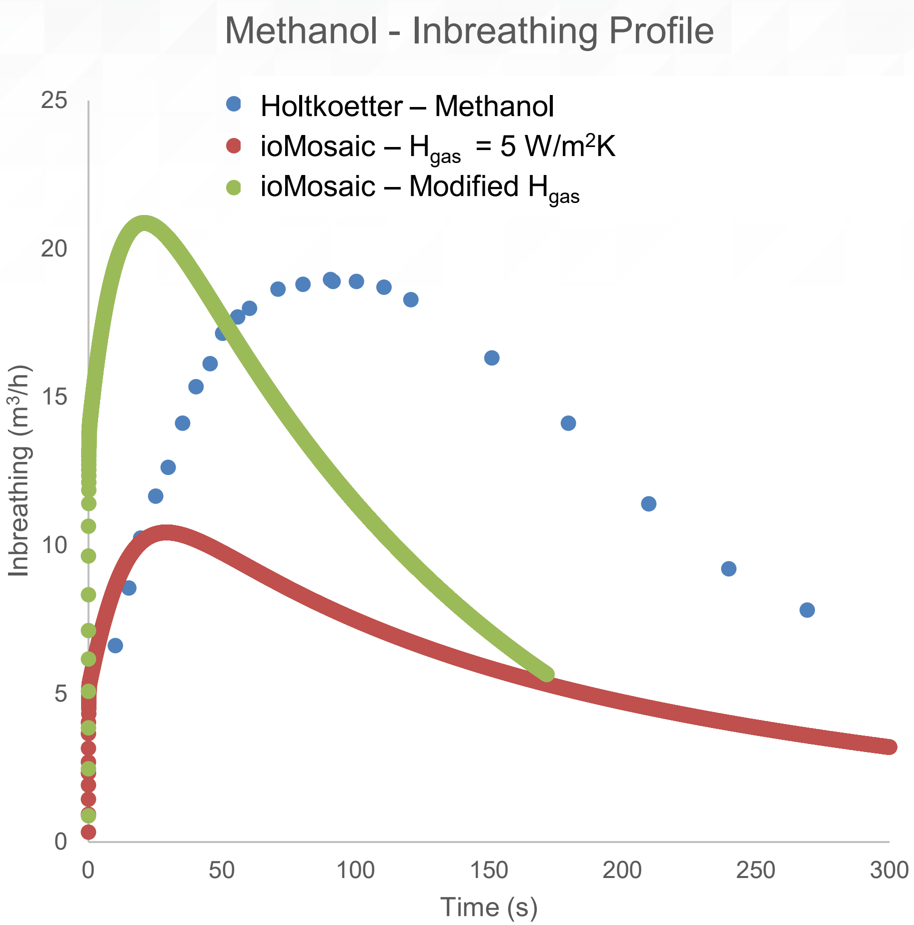



Source: Holtkötter, T., Shang, J. and Scheckerm, H.G. “Behälteratmung - Experimentelle Untersuchungen und Entwicklung eines Vorhersagemodells” (1997)

# Holtkoetter's Tank – Assumptions Used in SuperChems™

- Ambient Temperature = 10° C, Cloud Coverage = 0% (indoor experiment), Average Wind Speed = 2 m/s
- Location: Berlin, Germany (Longitude: 13.417 deg Latitude: 52.5 deg)
- Vessel: H = 1.5 m; D = 1 m; s = 1.2 mm; V = 1.18 $m^3$
- Initial Liquid Level = 0.15%
- Heat Transfer Coefficients:
- $H_{gas}$ = 5 $W/m^2K$ (Note: Holtkoetter did not measure this value)
- Rain intensity = 455 $kg/m_2h$ or 17.9 inch/h or $H_{rain}$ = 601 $W/m_2K$ (using Lloyd's Register rain correlation)

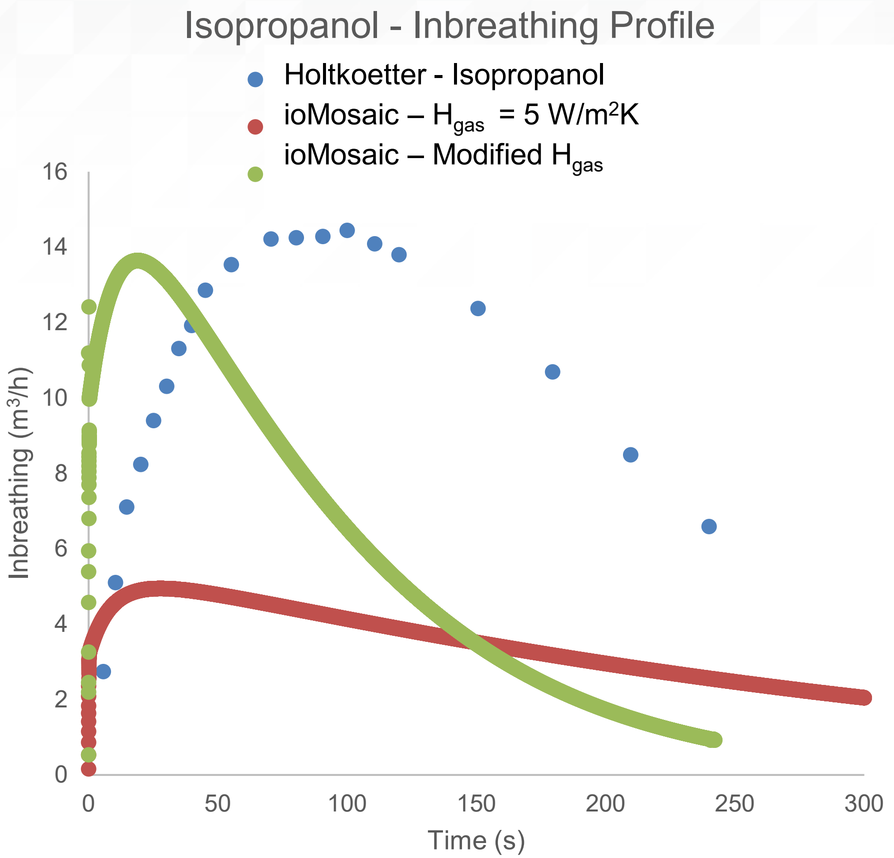
# Holtkoetter – Methanol – Replication in SuperChems™




| Input Parameters | |
|---|---|
| Hole size | 2” |
| $\Delta P_{max}$ | -0.004 psig |
| $H_{gas}$ | 30 W/m²K |
| $H_{rain}$ | 601 W/m²K |

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

# Holtkoetter – Isopropanol – Replication in SuperChems™




| Input Parameters | |
|---|---|
| Hole size | 2” |
| $\Delta P_{max}$ | -0.002 psig |
| $H_{gas}$ | 30 W/m²K |
| $H_{rain}$ | 601 W/m²K |

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation



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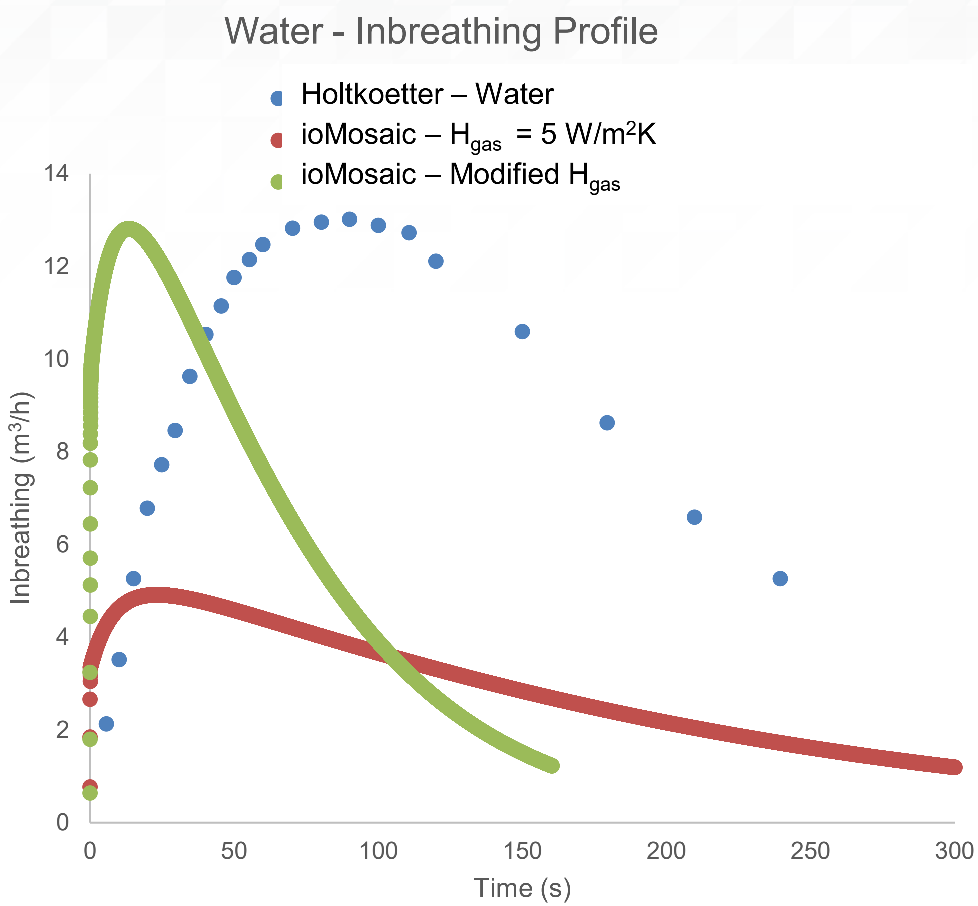
# Holtkoetter – Water – Replication in SuperChems™




| Input Parameters | |
|---|---|
| Hole size | 2” |
| $\Delta P_{max}$ | -0.004 psig |
| $H_{gas}$ | 30 W/m²K |
| $H_{rain}$ | 601 W/m²K |

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation



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# Holtkoetter assumed API 2000's constant value of 5W/m$^2$K for $h_{gas}$ for all types of vapors(condensable or not), however, he did not measure this value to validate it

- The table below shows the value of $h_{gas}$ used in order to match the experimental data obtained by Holtkoetter

| $h_{gas}$ (W/m$^2$K) | 1.2 mm Wall |
|---|---|
| Methanol | 30 |
| Isopropanol | 30 |
| Water | 30 |

# API 2000 Thermal Inbreathing relief equation is adequate for dry air but underpredicts the relief requirement for water, methanol, and ethanol vapors service in low-pressure storage tanks

| Vapor | $V_{max,\ SC}$ ($Nm^3/h$ of air) | $V_{max,\ API\ 2000}$ ($Nm^3/h$ of air) | % Deviation (API-Model)/Model | API 2000 Suitable? (Y/N) |
|---|---|---|---|---|
| Sigel Air | 104 | 440 | +214 | Y |
| Holtkoetter Water | 13 | 5.6 | -57 | N |
| Holtkoetter Isopropanol | 13.6 | 5.6 | -59 | N |
| Holtkoetter Methanol | 20.9 | 5.6 | -73 | N |
| Sigel Air | 104 | 440 | +214 | Y |
| Holtkoetter Water | 13 | 5.6 | -57 | N |

# Dynamic modeling of inbreathing relief requirements is recommended where condensable vapors are present

- The value of the internal (gas-wall) free convection heat transfer coefficient, $H_{gas}$, for condensable vapors is higher than the value of 5 W/m$^2$K used by API 2000
- API 2000 rain falling-film heat transfer coefficient has a very high value of 5,000 W/m$^2$K which leads to overdesign of relief requirements → economic loss
- API 2000 yields adequate relief requirements for non-condensable vapors such as air
- API 2000 may not be conservative (underpredicts thermal inbreathing requirements) for condensable vapors and condensable vapor mixtures

# References


- API Standard 2000, Venting Atmospheric and Low-Pressure Storage Tanks, 7th Edition, March 2014
- Fullarton, D., J. Evripidis and E.U. Shclünder, "Influence of Product Vapour Condensation on Venting of Storage Tanks", Institut für Thermische Verfahrenstechnik, Universität Karlsruhe (TH),Postfach 6980, D-7500 Karlsruhe 1, 1986
- Foerster, H., K. Schampel, and H. Steen, “Atmungsvorgänge infolge von Witterungseinflüssen an Lagertanks für brennbare Flüssigkeiten”, Physikalisch Technische Bundesanstalt (PTB) W-22. Braunschweig Univ. Phys.-Tech. Bundesanst, 1984
- Sigel, R., Kuxdorf, B., Meiss, R. and H. Schwarz, “Praktische und theoretische Untersuchung der Beatmung von Festdachtanks”. Chemie Ingenieur Technik, 55.5(1983): 377-379
- Holtkötter, T., Shang, J. and H.G. Scheckerm “Behälteratmung - Experimentelle Untersuchungen und Entwicklung eines Vorhersagemodells”. Chemie Ingenieur Technik, 69.3(1997): 361-366
- R. Scholz, and R. Weber. “Cooling Down Industrial Tanks”. Prepared for PROTEGO Braunschweiger Flammenfilter at API 2000 Meeting Presentation, Fall 2010
- D. Brooks “Thermal Inbreathing Requirements of Low Pressure Storage Tanks at Elevated Temperatures”. Lloyd’s Register Energy Americas, Inc. Spring DIERS Users Group Meeting, Presentation, May 2012

# About ioMosaic Corporation

Through innovation and dedication to continual improvement, ioMosaic has become a leading provider of integrated process safety and risk management solutions. ioMosaic has expertise in a wide variety of areas, including pressure relief systems design, process safety management, expert litigation support, laboratory services, training, and software development.

ioMosaic offers integrated process safety and risk management services to help you manage and reduce episodic risk. Because when safety, efficiency, and compliance are improved, you can sleep better at night. Our extensive expertise allows us the flexibility, resources, and capabilities to determine what you need to reduce and manage episodic risk, maintain compliance, and prevent injuries and catastrophic incidents.

Our mission is to help you protect your people, plant, stakeholder value, and our planet.

For more information on ioMosaic, please visit: **www.ioMosaic.com**