Report on the Final Results of ASHRAE RP-1767 “Transport Properties of Moist Air”

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Contents

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1. Introduction

- **State of the art:** only two imprecise figures of transport properties of moist air, based on outdated equations, available in the current ASHRAE Handbook Ch. 1
- **No ASHRAE Research Project was carried out on Transport Properties Research before RP-1767**
- ASHRAE funded RP-1485 „Thermodynamic Properties of Moist Air, Dry Air, Steam, Water, and Ice“, finished in 2009 -> „Gold Standard“ in Thermodynamics of Moist Air -> needed for the calculation of transport properties of moist air
- Extensive research on transport properties of dry air at NIST (2004)
- IAPWS sponsored significant research on transport properties of water and steam in the period from 1984 to 2014

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- An unsolicited research proposal was written and submitted in 2015 by S. Herrmann, H.-J. Kretzschmar, V.C. Aute, and D.P. Gatley
- Proposal was reviewed, accepted and PMC was installed
- ASHRAE RP-1767 started on 1st of July, 2016, and will last up to 31st of December, 2017; **Update:** an extension to the 30th of June, 2018 was requested

2. Recent Transport Properties Research

- New correlations for the viscosity and the thermal conductivity of dry air were published by Lemmon and Jacobsen (2004)
- A new correlation for viscosity of H_2O were released as International Standard by IAPWS (2008) based on research by Huber et al. at NIST
- A new correlation for thermal conductivity of H_2O were released as International Standard by IAPWS (2011) based on research by Huber et al. at NIST
- Revised correlations for thermodynamic properties of moist air were developed within the ASHRAE Research Project RP-1485 (Herrmann et al., 2009)
- Vesovic-Wakeham procedure to model viscosity and thermal conductivity for mixtures (1989, 1991)
- Significant advancement in measuring moist air transport properties at higher pressures and temperatures resulting from research typical of the Compressed Air Energy Storage (CAES) process (final model can be used from 243 K to 1000 K and pressures to 40 MPa), European Union Project AA-CAES (2002-2006)

3. Algorithms for Moist Air Transport Properties

Calculation of Viscosity of Moist Air

- Viscosity of gas mixures (Vesovic and Wakeham, 1989)

$$\eta_{\mathrm{mix}}(T,\rho_{\mathrm{m}},\bar{x}) = -\begin{vmatrix} H_{11} & \cdots & H_{1N} & Y_1 \\ \vdots & & \vdots & \vdots \\ H_{N1} & \cdots & H_{NN} & Y_N \\ Y_1 & \cdots & Y_N & 0 \end{vmatrix} \Bigg/ \begin{vmatrix} H_{11} & \cdots & H_{1N} \\ \vdots & & \vdots \\ H_{N1} & \cdots & H_{NN} \end{vmatrix} + \kappa_{\mathrm{mix}}$$

with $$Y_i = x_i\left(1+\sum_{j=1}^{N}\frac{m_j}{m_i+m_j}x_j\alpha_{ij}\bar{\chi}_{ij}\rho_{\mathrm{m}}\right)$$

$$H_{ii} = \frac{x_i^2\bar{\chi}_{ii}}{\eta_i^0} + \sum_{\substack{j=1\\ j\neq i}}^{N}\frac{x_i x_j\bar{\chi}_{ij}}{2A_{ij}^*\eta_{ij}^0}\frac{m_i m_j}{\left(m_i+m_j\right)^2}\left(\frac{20}{3}+\frac{4m_j}{m_i}A_{ij}^*\right)$$

$$H_{ij} = -\frac{x_i x_j\bar{\chi}_{ij}}{2A_{ij}^*\eta_{ij}^0}\frac{m_i m_j}{\left(m_i+m_j\right)^2}\left(\frac{20}{3}-4A_{ij}^*\right) \quad (i\neq j)$$

$$\kappa_{\mathrm{mix}} = \frac{16}{5\pi}\,\frac{15}{16}\rho_{\mathrm{m}}^2\sum_{i=1}^{N}\sum_{j=1}^{N}x_i x_j\bar{\chi}_{ij}\alpha_{ij}^2\eta_{ij}^0$$

- Contact value of the pseudo-radial distribution function for a pure component

$$\bar{\chi}_i(T,\rho_\mathrm{m}) = \frac{\beta_\eta\left(\eta_i - \rho_\mathrm{m}\alpha_{ii}\eta_i^0\right)}{2\rho_\mathrm{m}^2\alpha_{ii}^2\eta_i^0} \pm \beta_\eta\left[\left(\frac{\eta_i - \rho_\mathrm{m}\alpha_{ii}\eta_i^0}{2\rho_\mathrm{m}^2\alpha_{ii}^2\eta_i^0}\right)^2 - \frac{1}{\beta_\eta\rho_\mathrm{m}^2\alpha_{ii}^2}\right]^{1/2}$$

with α_{ii} from $\dfrac{\eta_i(T,\rho_\mathrm{m}^*)}{\rho_\mathrm{m}^*\alpha_{ii}\eta_i^0} = 1 + \dfrac{2}{\sqrt{\beta_\eta}}$ and $\left[\dfrac{\partial\eta_i(T,\rho_\mathrm{m})}{\partial\rho_\mathrm{m}}\right]_T = \dfrac{\eta_i(T,\rho_\mathrm{m}^*)}{\rho_\mathrm{m}^*}$,

$\dfrac{1}{\beta_\eta} = \dfrac{1}{4} + \left(\dfrac{16}{5\pi}\right)\dfrac{15}{16}$ and ρ_m^* as switch-over density

- Mixing rules

$$\bar{\chi}_{ij} = 1 + \frac{2}{5}\sum_{k=1}^{N} x_k\left(\bar{\chi}_k - 1\right) + \frac{\frac{6}{5}\left(\bar{\chi}_i - 1\right)^{1/3}\left(\bar{\chi}_j - 1\right)^{1/3}\sum\limits_{k=1}^{N} x_k\left(\bar{\chi}_k - 1\right)^{2/3}}{\left(\bar{\chi}_i - 1\right)^{1/3} + \left(\bar{\chi}_j - 1\right)^{1/3}}$$

$$\alpha_{ij} = \frac{1}{8}\left(\alpha_{ii}^{1/3} + \alpha_{jj}^{1/3}\right)^3$$

Calculation of Thermal Conductivity of Moist Air

- Thermal Conductivity of gas mixures (Vesovic and Wakeham, 1991)

$$\lambda_\mathrm{mix}(T,\rho_\mathrm{m},\bar{x}) = \lambda_\mathrm{mix}(\mathrm{mon})(T,\rho_\mathrm{m},\bar{x}) + \lambda_\mathrm{mix}(\mathrm{int})(T,\rho_\mathrm{m},\bar{x})$$

Internal (int) contribution

$$\lambda_\mathrm{mix}(\mathrm{int})(T,\rho_\mathrm{m},\bar{x}) = \sum_{i=1}^{N}\left[\frac{\lambda_i^0 - \lambda_i^0(\mathrm{mon})}{\bar{\chi}_{ii}}\right]\left[1 + \sum_{\substack{j=1\\ j\neq i}}^{N}\frac{x_j\lambda_i^0(\mathrm{mon})\bar{\chi}_{ij}A_{ii}^*}{x_i\lambda_{ij}^0(\mathrm{mon})\bar{\chi}_{ii}A_{ij}^*}\right]^{-1}$$

Monatomic (mon) contribution

$$\lambda_\mathrm{mix}(\mathrm{mon})(T,\rho_\mathrm{m},\bar{x}) = -\begin{vmatrix} L_{11} & \cdots & L_{1N} & Y_1 \\ \vdots & & \vdots & \vdots \\ L_{N1} & \cdots & L_{NN} & Y_N \\ Y_1 & \cdots & Y_N & 0 \end{vmatrix} \Bigg/ \begin{vmatrix} L_{11} & \vdots & L_{1N} \\ \vdots & & \vdots \\ L_{N1} & \cdots & L_{NN} \end{vmatrix} + \kappa_\mathrm{mix}$$

$$Y_i = x_i\left[1+\sum_{j=1}^{N}\frac{2m_i m_j}{\left(m_i+m_j\right)^2}x_j\gamma_{ij}\bar{\chi}_{ij}\rho_{\mathrm{m}}\right]$$

$$L_{ii} = \frac{x_i^2\bar{\chi}_{ii}}{\lambda_i^0(\mathrm{mon})}+\sum_{\substack{j=1\\ j\neq i}}^{N}\left[\frac{x_i x_j\bar{\chi}_{ij}}{2A_{ij}^*\lambda_{ij}^0(\mathrm{mon})\left(m_i+m_j\right)^2}\left(\frac{15}{2}m_i^2+\frac{25}{4}m_j^2-3m_j^2B_{ij}^*+4m_i m_j A_{ij}^*\right)\right]$$

$$L_{ij} = -\frac{x_i x_j\bar{\chi}_{ij}}{2A_{ij}^*\lambda_{ij}^0(\mathrm{mon})}\frac{m_i m_j}{\left(m_i+m_j\right)^2}\left(\frac{55}{4}-3B_{ij}^*-4A_{ij}^*\right)\quad\left(i\neq j\right)$$

$$\kappa_{\mathrm{mix}} = \frac{16}{5\pi}\frac{10}{9}\rho_{\mathrm{m}}^2\sum_{i=1}^{N}\sum_{j=1}^{N}\frac{m_i m_j}{\left(m_i+m_j\right)^2}x_i x_j\bar{\chi}_{ij}\gamma_{ij}^2\lambda_{ij}^0(\mathrm{mon})$$

and

$$\lambda_i^0(\mathrm{mon}) = \frac{5}{2}\left[\frac{c_{V\mathrm{m}}^{\mathrm{o}}(\mathrm{mon})}{M_i}\right]\eta_i^0,\qquad \lambda_{ij}^0(\mathrm{mon}) = \frac{5}{2}\left[\frac{c_{V\mathrm{m}}^{\mathrm{o}}(\mathrm{mon})}{M_{ij}}\right]\eta_{ij}^0$$

- Contact value of the pseudo-radial distribution function for a pure component

$$\bar{\chi}_i(T,\rho_{\mathrm{m}}) = \frac{\beta_\lambda\left[\lambda_i-\rho_{\mathrm{m}}\gamma_{ii}\lambda_i^0(\mathrm{mon})\right]}{2\rho_{\mathrm{m}}^2\gamma_{ii}^2\lambda_i^0(\mathrm{mon})}\pm\beta_\lambda\left\{\left[\frac{\lambda_i-\rho_{\mathrm{m}}\gamma_{ii}\lambda_i^0(\mathrm{mon})}{2\rho_{\mathrm{m}}^2\gamma_{ii}^2\lambda_i^0(\mathrm{mon})}\right]^2-\frac{\lambda_i^0}{\beta_\lambda\rho_{\mathrm{m}}^2\gamma_{ii}^2\lambda_i^0(\mathrm{mon})}\right\}^{1/2}$$

with γ_{ii} from $\dfrac{\lambda_i(T,\rho_{\mathrm{m}}^*)}{\rho_{\mathrm{m}}^*\gamma_{ii}\lambda_i^0(\mathrm{mon})} = 1+\dfrac{2}{\sqrt{\beta_\lambda}}\left[\dfrac{\lambda_i^0}{\lambda_i^0(\mathrm{mon})}\right]^{1/2}$ and $\left[\dfrac{\partial\lambda_i(T,\rho_{\mathrm{m}})}{\partial\rho_{\mathrm{m}}}\right]_T = \dfrac{\lambda_i(T,\rho_{\mathrm{m}}^*)}{\rho_{\mathrm{m}}^*}$,

$\dfrac{1}{\beta_\lambda} = \dfrac{1}{4}+\left(\dfrac{16}{5\pi}\right)\dfrac{5}{18}$ and ρ_{m}^* as switch-over density

- Mixing rules

$$\bar{\chi}_{ij} = 1+\frac{2}{5}\sum_{k=1}^{N}x_k\left(\bar{\chi}_k-1\right)+\frac{\frac{6}{5}\left(\bar{\chi}_i-1\right)^{1/3}\left(\bar{\chi}_j-1\right)^{1/3}\sum_{k=1}^{N}x_k\left(\bar{\chi}_k-1\right)^{2/3}}{\left(\bar{\chi}_i-1\right)^{1/3}+\left(\bar{\chi}_j-1\right)^{1/3}}$$

$$\alpha_{ij} = \frac{1}{8}\left(\alpha_{ii}^{1/3}+\alpha_{jj}^{1/3}\right)^3$$

Implementation of Vesovic-Wakeham Mixing Models for Moist Air

- Treatment of critical enhancement for pure components

$$\eta_i(T,\rho_\mathrm{m}) = \eta_{i,\mathrm{total}}(T,\rho_\mathrm{m}) - \eta_i^\mathrm{C}(T,\rho_\mathrm{m})$$

$$\lambda_i(T,\rho_\mathrm{m}) = \lambda_{i,\mathrm{total}}(T,\rho_\mathrm{m}) - \lambda_i^\mathrm{C}(T,\rho_\mathrm{m})$$

► critical enhancement subtracted from total value for pure fluid
-> performed for water only, since dry air far away from critical point

$$\lambda_{\mathrm{mix,total}}(T,\rho_\mathrm{m}) = \lambda_\mathrm{mix}(T,\rho_\mathrm{m}) + \lambda_\mathrm{w}^\mathrm{C}(T,\rho_\mathrm{m,w})$$

► critical enhancement for thermal conductivity of water added after mixing

- Calculation of water as hypothetical fluid

► water could become a liquid under pressure and temperature of moist air
-> treated as hypothetical fluid for (T<T_c) and (ρ_m >ρ_ms) as follows

$$\eta_\mathrm{w}(T,\rho_\mathrm{m}) = \eta_\mathrm{w}(T,\rho_\mathrm{ms}) + \left[\eta_\mathrm{w}(T_\mathrm{ref},\rho_\mathrm{m}) - \eta_\mathrm{w}(T_\mathrm{ref},\rho_\mathrm{ms})\right]$$

$$\lambda_\mathrm{w}(T,\rho_\mathrm{m}) = \lambda_\mathrm{w}(T,\rho_\mathrm{ms}) + \left[\lambda_\mathrm{w}(T_\mathrm{ref},\rho_\mathrm{m}) - \lambda_\mathrm{w}(T_\mathrm{ref},\rho_\mathrm{ms})\right]$$

with T_ref = 650 K and ρ_ms as saturated vapor molar density at given temperature

- Quantities for interaction of unlike molecules

► based on extended corresponding states principle
► scaling factors resulting for pure components of dry air and water
with following mixing rules:

$$\sigma_{ij} = \frac{1}{2}\left(\sigma_{ii} + \sigma_{jj}\right) \qquad \varepsilon_{ij} = \frac{1}{2}\left(\varepsilon_{ii}\varepsilon_{jj}\right)^{1/2}$$

$$\Rightarrow \quad \sigma_{ij} = 0.31562\ \mathrm{nm\ and}\ \varepsilon_{ij}/k_\mathrm{B} = 276.28\ \mathrm{K}$$

► interaction viscosity in the limit of zero density follows from

$$\eta_{ij}^0(T) = \frac{0.021357\left(\dfrac{2M_iM_j}{M_i+M_j}T\right)^{1/2}}{\sigma_{ij}^2 S_\eta^*(T_{ij}^*)}$$

with $\ln S_\eta^*(T_{ij}^*) = \sum_{k=0}^{4} a_k\left[\ln\left(T_{ij}^*\right)\right]^k$ and $T_{ij}^* = \dfrac{k_\mathrm{B}\,T}{\varepsilon_{ij}}$

► A_{ij}^* and B_{ij}^* are to be 1.1, each

Improvement of Vesovic-Wakeham Model Using Experimental Data

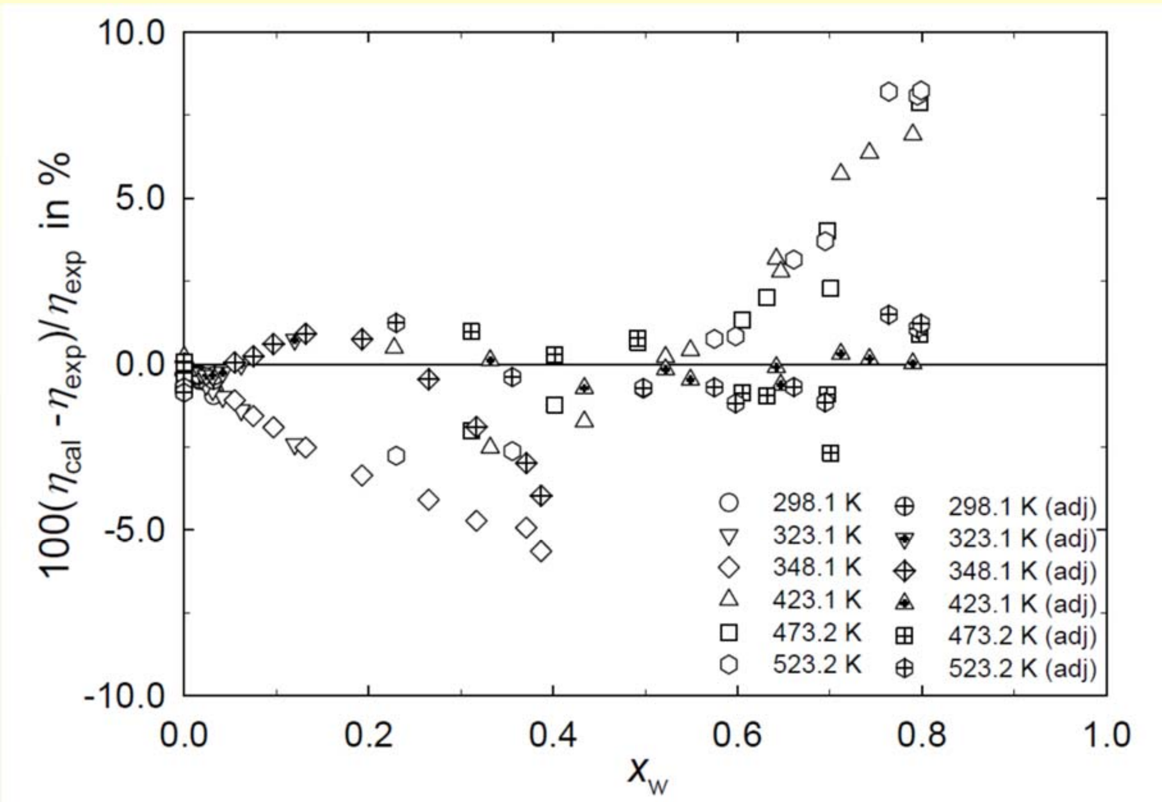
- Adjustment of length scaling factor
  - ► molecules of dry air and water do not correspond to spherically symmetric interaction potentials -> theorem of corresponding states inappropriate for interaction viscosity in the limit of zero densiy
  - ► interaction viscosity now treated as function of mole fraction of water
  - ► fitted to experimental data by Kestin and Whitelaw as well as by Hochrainer and Munczak resulting in

$$\sigma_{ij}^{\mathrm{adj}}(x_{\mathrm{w}}) = \sigma_{ij}\left[1 + x_1 x_2 \sum_{k=0}^{n} b_k (x_1 - x_2)^k\right]$$

where coefficients b_k adjusted with n = 2

Result of Improvement of Vesovic-Wakeham Model Using Experimental Data

- Kestin and Whitelaw (1964): viscosity of moist air at atmospheric pressure



4. Deliverables of ASHRAE RP-1767

4.1 Deliverable 1: New SI and I-P moist air property tables

New SI and I-P moist air property tables for the ASHRAE Handbook of Fundamentals, Psychrometrics Chapter

Transport Properties of Moist Air at Atmospheric Pressure (p = 101.325 kPa)

Temp., °C t	Absolute Humidity W_s, kg_w/kg_{da}	Density, kg/m³ ρ_{da}	Density, kg/m³ ρ_s	Viscosity, µPa s η_{da}	Viscosity, µPa s η_s	Kinematic Viscosity, 10^{-6} m²/s ν_{da}	Kinematic Viscosity, 10^{-6} m²/s ν_s	Thermal Cond., mW/(m K) λ_{da}	Thermal Cond., mW/(m K) λ_s	Prandtl Number (-) Pr_{da}	Prandtl Number (-) Pr_s	Temp., °C t
0	0.00379	1.293	1.290	17.22	17.18	13.32	13.32	0.02436	0.02433	0.7108	0.7124	0
1	0.00408	1.288	1.285	17.27	17.23	13.40	13.40	0.02444	0.02441	0.7107	0.7124	1
2	0.00438	1.284	1.280	17.32	17.27	13.49	13.49	0.02451	0.02448	0.7105	0.7124	2
3	0.00471	1.279	1.275	17.37	17.32	13.58	13.58	0.02459	0.02455	0.7104	0.7124	3
4	0.00505	1.274	1.271	17.42	17.37	13.67	13.67	0.02467	0.02463	0.7102	0.7124	4
5	0.00542	1.270	1.266	17.47	17.41	13.76	13.76	0.02474	0.02470	0.7101	0.7124	5
6	0.00582	1.265	1.261	17.52	17.46	13.85	13.85	0.02482	0.02478	0.7099	0.7124	6
7	0.00624	1.261	1.256	17.57	17.51	13.93	13.94	0.02489	0.02485	0.7098	0.7124	7
8	0.00668	1.256	1.251	17.62	17.55	14.02	14.03	0.02497	0.02493	0.7096	0.7124	8
9	0.00716	1.252	1.246	17.67	17.60	14.11	14.12	0.02505	0.02500	0.7095	0.7125	9
10	0.00766	1.247	1.242	17.72	17.65	14.20	14.21	0.02512	0.02507	0.7093	0.7126	10
11	0.00820	1.243	1.237	17.76	17.69	14.29	14.30	0.02520	0.02515	0.7092	0.7126	11
12	0.00877	1.239	1.232	17.81	17.74	14.38	14.40	0.02527	0.02522	0.7090	0.7127	12
13	0.00937	1.234	1.227	17.86	17.78	14.47	14.49	0.02535	0.02530	0.7089	0.7128	13
14	0.01001	1.230	1.223	17.91	17.83	14.56	14.58	0.02542	0.02537	0.7088	0.7130	14
15	0.01069	1.226	1.218	17.96	17.87	14.66	14.67	0.02550	0.02545	0.7086	0.7131	15
16	0.01142	1.221	1.213	18.01	17.92	14.75	14.77	0.02557	0.02552	0.7085	0.7132	16
17	0.01218	1.217	1.208	18.06	17.96	14.84	14.86	0.02565	0.02559	0.7083	0.7134	17
18	0.01299	1.213	1.204	18.11	18.00	14.93	14.96	0.02572	0.02567	0.7082	0.7136	18
19	0.01385	1.209	1.199	18.16	18.05	15.02	15.05	0.02580	0.02575	0.7081	0.7138	19
20	0.01476	1.205	1.194	18.21	18.09	15.11	15.15	0.02587	0.02582	0.7079	0.7140	20
21	0.01572	1.200	1.189	18.25	18.14	15.21	15.25	0.02595	0.02590	0.7078	0.7143	21

Old Figure 12 of the current ASHRAE Handbook of Fundamentals, Psychrometrics Chapter, showing viscosity values for moist air

Regions below red lines are the liquid and ice fog regions.

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Mixture model is needed to calculate viscosity in this region!

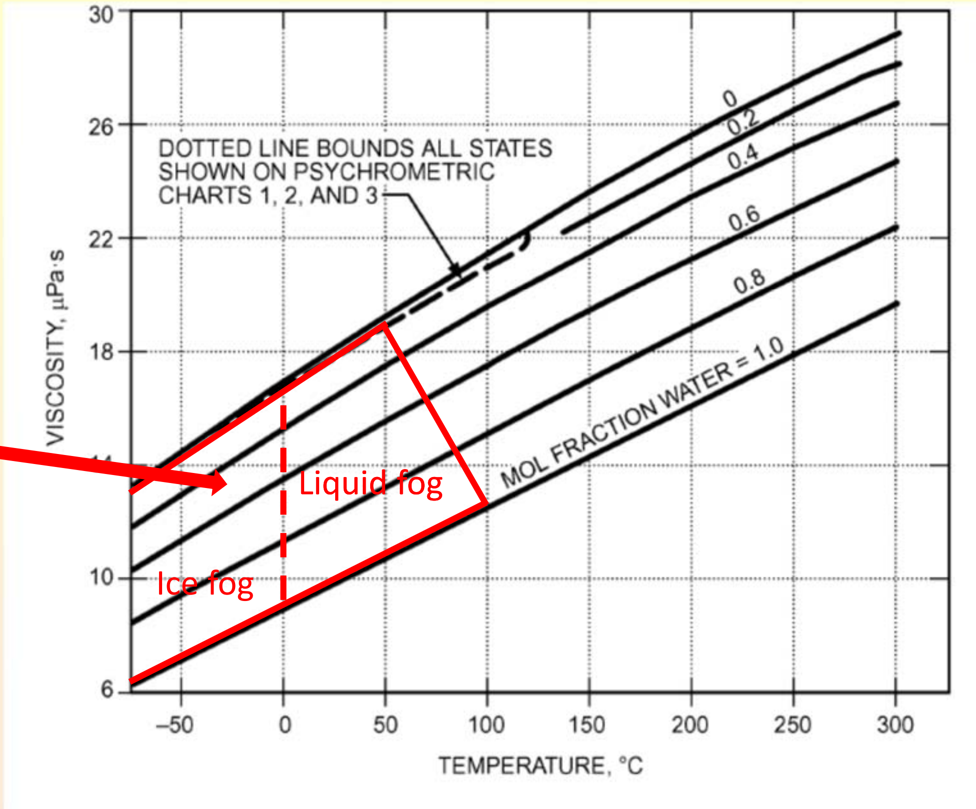
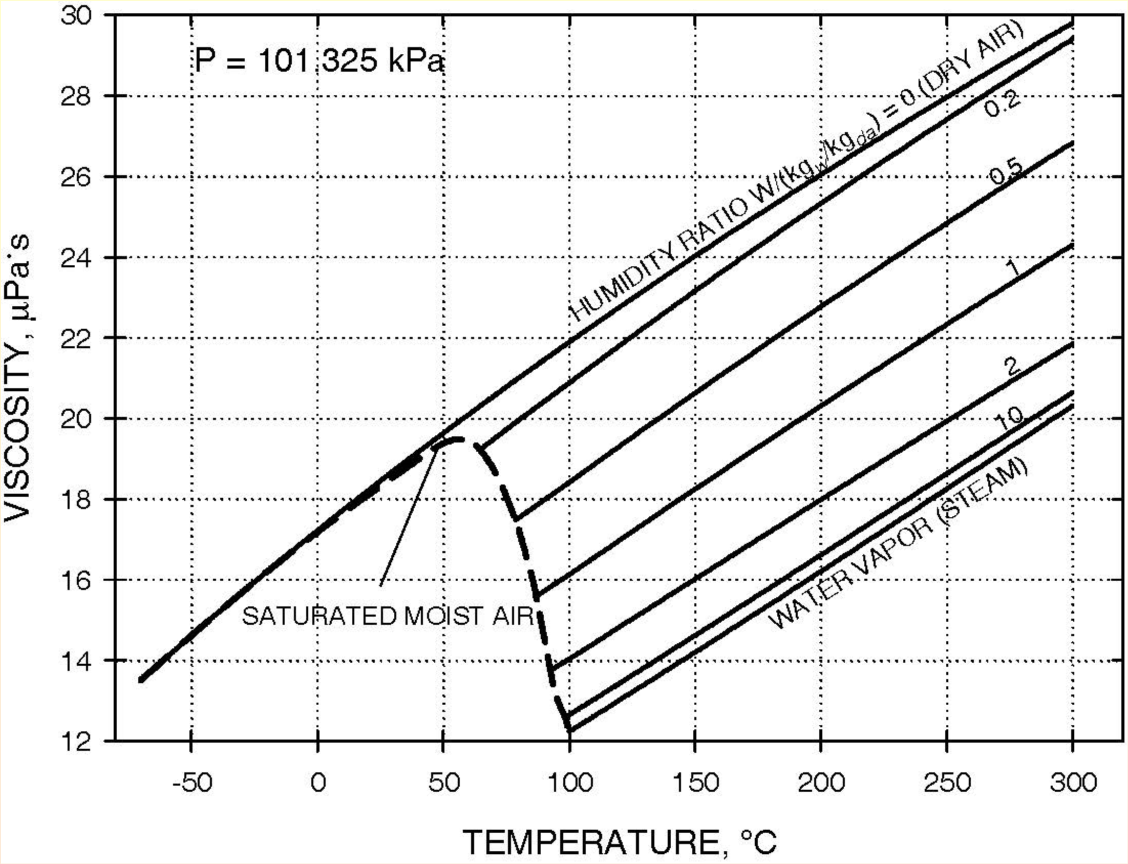


Fig. 12 Viscosity of Moist Air

4.2 Deliverable 2: New Figures for Transport Properties of Moist Air

New Figure 12 for the ASHRAE Handbook of Fundamentals, Psychrometrics Chapter, showing viscosity values for moist air



Old Figure 13 of the current ASHRAE Handbook of Fundamentals, Psychrometrics Chapter, showing thermal conductivity values for moist air

Regions below red lines are the liquid and ice fog regions.

Mixture model is needed to calculate thermal conductivity in this region!

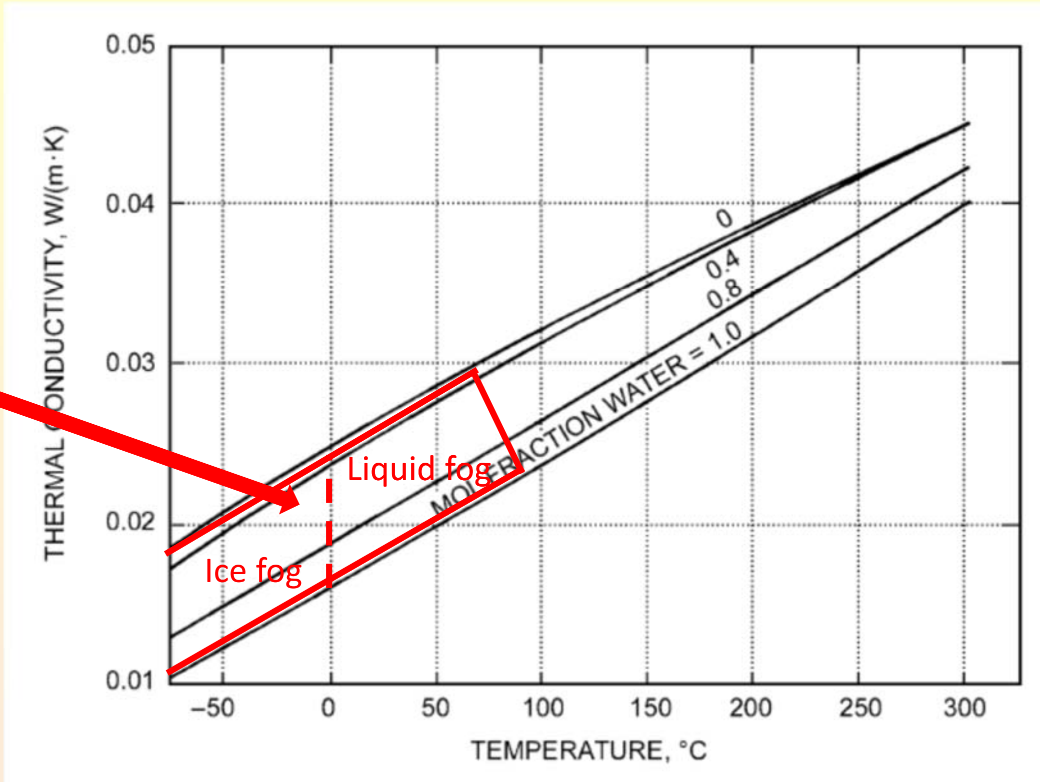
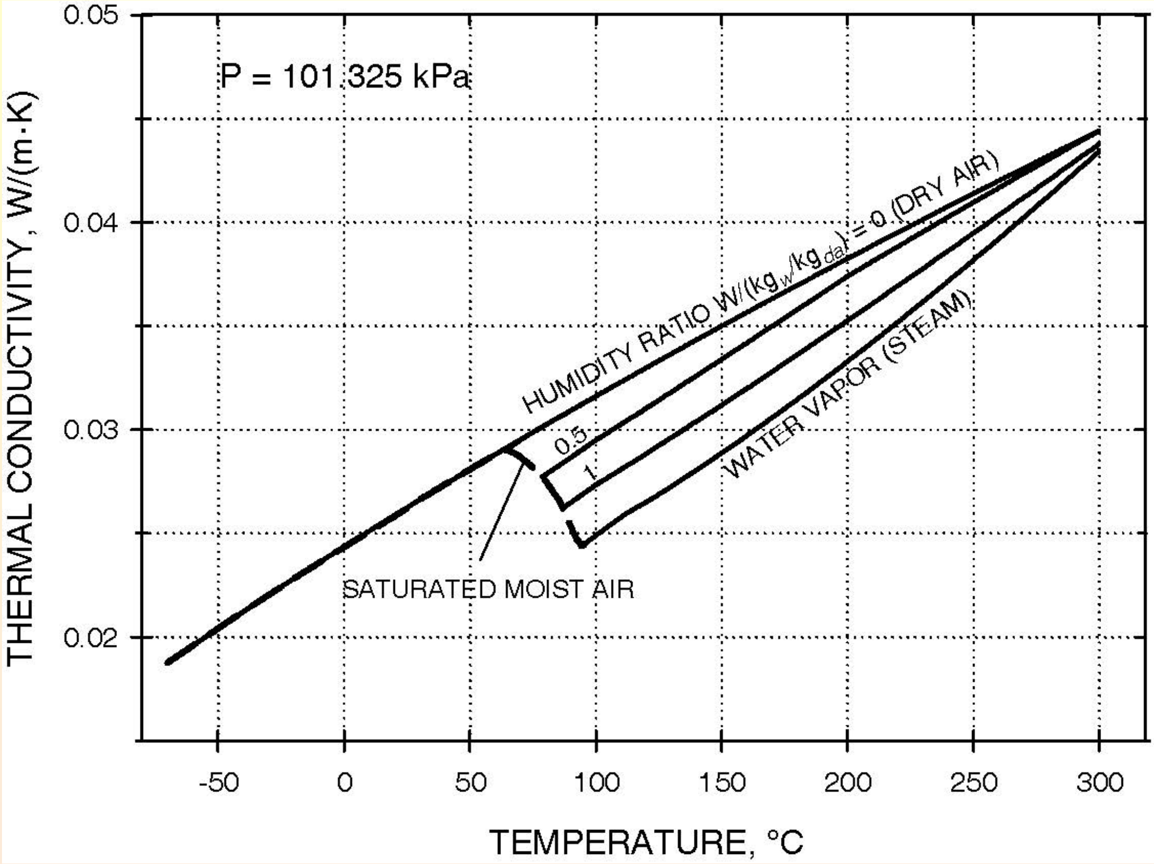


Fig. 13 Thermal Conductivity of Moist Air

New Figure 13 for the ASHRAE Handbook of Fundamentals, Psychrometrics Chapter, showing thermal conductivity values for moist air



4.3 Deliverable 3: Comparison of new algorithms

Comparison of new algorithms for viscosity of moist air to the former equations by Mason and Monchick (1965)

Relative deviations of the data of Mason and Monchick from the values, calculated from ASHRAE RP-1767, in percent

Viscosity	Mole Fraction H20										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Temperature	Absolute Humidity (converted from Mole Fraction H2O)										
(°C)	0	0.06910504	0.15548633	0.26654799	0.41463021	0.62194532	0.93291797	1.45120574	2.48778126	5.59750784	1000000000
-80											
-70	-0.30										
-60	-0.26										
-50	-0.23										
-40	-0.21										
-30	-0.26										
-20	-0.25										
-10	-0.26					supersaturated moist air					
0	-0.28										
10	-0.31										
20	-0.31										
30	-0.37										
40	-0.44										
50	-0.49	-0.53									
60	-0.49	-0.71									
70	-0.52	-0.85	-0.49	1.97							
80	-0.57	-1.00	-0.74	1.64	4.42						
90	-0.63	-1.17	-0.95	1.34	4.05	6.37	8.85				
100	-0.71	-1.31	-1.22	1.04	3.73	5.99	8.50	11.44	12.70	8.52	1.86
120	-0.80	-1.61	-1.69	0.42	2.98	5.14	7.57	10.48	11.78	7.78	1.32
140	-0.89	-1.90	-2.12	-0.11	2.32	4.37	6.72	9.64	10.88	7.00	0.76
160	-1.02	-2.17	-2.49	-0.66	1.64	3.68	5.93	8.78	10.08	6.28	0.20
180	-1.11	-2.40	-2.88	-1.15	1.07	2.99	5.20	8.03	9.35	5.66	-0.28
200	-1.25	-2.67	-3.27	-1.62	0.51	2.37	4.52	7.31	8.58	4.97	-0.82
220	-1.37	-2.90	-3.58	-2.05	0.00	1.79	3.88	6.63	7.95	4.34	-1.34
240	-1.49	-3.13	-3.89	-2.44	-0.51	1.25	3.29	6.03	7.28	3.76	-1.84
260	-1.57	-3.31	-4.17	-2.83	-0.93	0.75	2.77	5.46	6.72	3.22	-2.31
280	-1.59	-3.43	-4.39	-3.12	-1.29	0.29	2.28	4.91	6.18	2.74	-2.70
300	-1.58	-3.51	-4.56	-3.39	-1.63	-0.08	1.85	4.47	5.70	2.29	-3.07

Tabulated values are calculated as follows: $(\eta_{MaMo65}-\eta_{RP1767})/\eta_{RP1767}*100$

Comparison of new algorithms for thermal conductivity of moist air to the former equations by Mason and Monchick (1965)

Relative deviations of the data of Mason and Monchick from the values, calculated from ASHRAE RP-1767, in percent

Thermal Conductivity	Mole Fraction H20										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Temperature	Absolute Humidity (converted from Mole Fraction H2O)										
(°C)	0	0.06910504	0.15548633	0.26654799	0.41463021	0.62194532	0.93291797	1.45120574	2.48778126	5.59750784	1000000000
-80											
-70	-3.02										
-60	-2.86										
-50	-2.66										
-40	-2.42										
-30	-2.16										
-20	-2.06										
-10	-1.74					supersaturated moist air					
0	-1.59										
10	-1.40										
20	-1.36										
30	-1.13										
40	-0.88										
50	-0.77	-0.18									
60	-0.64	-0.06									
70	-0.50	0.07	-1.82	-2.74							
80	-0.33	0.22	-1.79	-2.80	-1.63						
90	-0.29	0.25	-1.75	-2.87	-1.79	-0.54	-0.08				
100	-0.10	-1.31	-1.76	0.07	2.01	3.24	4.41	5.78	5.20	-0.08	-7.13
120	0.07	-1.37	-2.00	-0.20	1.78	2.96	4.15	5.78	5.40	0.43	-6.23
140	0.16	-1.37	-2.08	-0.45	1.39	2.62	3.91	5.55	5.43	0.66	-5.58
160	0.32	-1.45	-2.25	-0.80	1.00	2.23	3.44	5.17	5.09	0.57	-5.49
180	0.51	-1.49	-2.49	-1.12	0.51	1.71	2.93	4.70	4.72	0.39	-5.56
200	0.64	-1.59	-2.69	-1.51	0.15	1.19	2.39	4.16	4.24	-0.10	-5.86
220	0.70	-1.65	-2.96	-1.87	-0.29	0.69	1.85	3.59	3.55	-0.57	-6.21
240	0.79	-1.77	-3.19	-2.19	-0.80	0.10	1.20	2.88	2.95	-1.25	-6.79
260	0.82	-1.86	-3.47	-2.57	-1.28	-0.45	0.56	2.17	2.20	-1.87	-7.36
280	0.89	-2.00	-3.72	-2.91	-1.71	-0.98	-0.05	1.47	1.55	-2.53	-7.99
300	0.88	-2.11	-4.01	-3.40	-2.30	-1.57	-0.73	0.79	0.70	-3.31	-8.66

Tabulated values are calculated as follows: $(\lambda_{MaMo65}-\lambda_{RP1767})/\lambda_{RP1767}*100$

4.4 Deliverable 4: Tables of Transport Properties of Water at Saturation

ASHRAE Handbook Fundamentals, Ch. 1: Table *Transport Properties of Water at Saturation* (SI Edition)

Transport Properties of Water at Saturation

Temp., °C	Absolute Pressure	Density, kg/m³		Viscosity, µPa s		Kinematic Viscosity, 10^{-6} m²/s		Thermal Cond., mW/(m K)		Prandtl Number (-)		Temp., °C
t	p_{ws}, kPa	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	t
0	0.6112127	999.79	0.00485	1792.0	8.945	1.792	1844	555.6	16.76	13.61	1.0078	0
1	0.65709	999.85	0.00520	1731.2	8.974	1.731	1727	558.1	16.82	13.08	1.0075	1
2	0.70599	999.89	0.00556	1673.7	9.003	1.674	1618	560.6	16.89	12.58	1.0073	2
3	0.75808	999.92	0.00595	1619.2	9.032	1.619	1517	563.0	16.95	12.11	1.0070	3
4	0.81355	999.93	0.00636	1567.4	9.061	1.568	1424	565.4	17.02	11.67	1.0068	4
5	0.87257	999.92	0.00680	1518.3	9.090	1.518	1336	567.7	17.08	11.25	1.0066	5
6	0.93535	999.89	0.00727	1471.6	9.120	1.472	1255	570.0	17.15	10.85	1.0064	6
7	1.0021	999.86	0.00776	1427.2	9.149	1.427	1180	572.2	17.21	10.48	1.0062	7
8	1.0730	999.80	0.00828	1384.8	9.179	1.385	1109	574.4	17.28	10.12	1.0061	8
9	1.1483	999.73	0.00883	1344.5	9.209	1.345	1043	576.6	17.35	9.787	1.0059	9
10	1.2282	999.65	0.00941	1306.0	9.238	1.306	982.1	578.7	17.41	9.469	1.0058	10
11	1.3129	999.56	0.01002	1269.2	9.268	1.270	924.9	580.8	17.48	9.166	1.0057	11
12	1.4028	999.45	0.01067	1234.1	9.299	1.235	871.5	582.8	17.55	8.878	1.0056	12
13	1.4981	999.33	0.01135	1200.5	9.329	1.201	821.6	584.8	17.61	8.605	1.0056	13
14	1.5989	999.20	0.01208	1168.4	9.359	1.169	774.9	586.8	17.68	8.344	1.0055	14
15	1.7057	999.05	0.01284	1137.6	9.390	1.139	731.3	588.7	17.75	8.095	1.0055	15
16	1.8188	998.90	0.01364	1108.1	9.420	1.109	690.4	590.6	17.81	7.858	1.0055	16
17	1.9383	998.73	0.01449	1079.9	9.451	1.081	652.2	592.5	17.88	7.632	1.0055	17
18	2.0647	998.55	0.01538	1052.7	9.482	1.054	616.4	594.4	17.95	7.415	1.0055	18
19	2.1982	998.36	0.01632	1026.7	9.513	1.028	582.8	596.2	18.02	7.208	1.0056	19
20	2.3392	998.16	0.01731	1001.6	9.544	1.003	551.3	598.0	18.09	7.010	1.0056	20
21	2.4881	997.95	0.01835	977.6	9.575	0.9796	521.7	599.7	18.16	6.821	1.0057	21

4.5 Deliverable 5: Update of Table for Refrigerant 718 (water/steam)

ASHRAE Handbook Fundamentals, Ch. 30: Table *Refrigerant 718 (Water/Steam) Properties of Saturated Liquid and Saturated Vapor* (SI Edition)

Refrigerant 718 (Water/Steam) Properties of Saturated Liquid and Saturated Vapor

Temp.,* °C	Pressure, MPa	Density, kg/m³ Liquid	Volume, m³/kg Vapor	Enthalpy, kJ/kg Liquid	Enthalpy, kJ/kg Vapor	Entropy, kJ/(kg·K) Liquid	Entropy, kJ/(kg·K) Vapor	Specific Heat c_p, kJ/(kg·K) Liquid	Specific Heat c_p, kJ/(kg·K) Vapor	c_p/c_v Vapor	Velocity of Sound, m/s Liquid	Velocity of Sound, m/s Vapor	Viscosity, µPa·s Liquid	Viscosity, µPa·s Vapor	Thermal Cond., mW/(m·K) Liquid	Thermal Cond., mW/(m·K) Vapor	Surface Tension, mN/m	Temp.,* °C
0.01[a]	0.0006117	999.79	205.997	0.00	2500.9	0.0000	9.1555	4.2199	1.8882	1.3277	1402.3	408.89	1791.4	8.946	555.6	16.76	75.646	0.01
5	0.00087	999.92	147.017	21.02	2510.1	0.0763	9.0249	4.2054	1.8917	1.3276	1426.0	412.53	1518.3	9.090	567.7	17.08	74.942	5
10	0.00123	999.65	106.309	42.02	2519.2	0.1511	8.8998	4.1958	1.8957	1.3275	1447.4	416.13	1306.0	9.238	578.7	17.41	74.221	10
15	0.00171	999.05	77.8807	62.98	2528.4	0.2245	8.7804	4.1894	1.9004	1.3274	1466.4	419.68	1137.6	9.390	588.7	17.75	73.486	15
20	0.00234	998.16	57.7615	83.92	2537.5	0.2965	8.6661	4.1851	1.9057	1.3273	1483.3	423.18	1001.6	9.544	598.0	18.09	72.736	20
25	0.00317	997.00	43.3414	104.84	2546.5	0.3673	8.5568	4.1822	1.9116	1.3272	1498.0	426.63	890.0	9.701	606.5	18.43	71.972	25
30	0.00425	995.61	32.8816	125.75	2555.6	0.4368	8.4521	4.1803	1.9180	1.3272	1510.8	430.04	797.2	9.860	614.3	18.79	71.194	30
35	0.00563	994.00	25.2078	146.64	2564.6	0.5052	8.3518	4.1792	1.9249	1.3272	1521.8	433.40	719.1	10.022	621.7	19.14	70.402	35
40	0.00738	992.18	19.5170	167.54	2573.5	0.5724	8.2557	4.1788	1.9322	1.3272	1531.1	436.72	652.7	10.185	628.4	19.51	69.596	40
45	0.00959	990.18	15.2534	188.44	2582.5	0.6386	8.1634	4.1790	1.9400	1.3274	1538.9	439.98	595.8	10.350	634.7	19.88	68.777	45
50	0.01235	988.01	12.0279	209.34	2591.3	0.7038	8.0749	4.1798	1.9482	1.3276	1545.2	443.20	546.5	10.516	640.6	20.26	67.944	50
55	0.01576	985.67	9.5649	230.24	2600.1	0.7680	7.9899	4.1811	1.9570	1.3280	1550.1	446.37	503.6	10.684	646.0	20.65	67.098	55
60	0.01995	983.18	7.6677	251.15	2608.8	0.8312	7.9082	4.1829	1.9664	1.3284	1553.7	449.50	466.0	10.854	651.0	21.04	66.238	60
65	0.02504	980.53	6.1938	272.08	2617.5	0.8935	7.8296	4.1853	1.9764	1.3290	1556.2	452.56	432.9	11.024	655.6	21.45	65.366	65
70	0.03120	977.75	5.0397	293.02	2626.1	0.9550	7.7540	4.1882	1.9873	1.3297	1557.5	455.57	403.5	11.195	659.7	21.86	64.481	70
75	0.03860	974.83	4.1291	313.97	2634.6	1.0156	7.6812	4.1917	1.9990	1.3306	1557.7	458.52	377.4	11.367	663.5	22.28	63.583	75
80	0.04741	971.78	3.4053	334.95	2643.0	1.0754	7.6110	4.1956	2.0119	1.3316	1557.0	461.41	354.0	11.539	667.0	22.72	62.673	80
85	0.05787	968.60	2.8259	355.95	2651.3	1.1344	7.5434	4.2001	2.0260	1.3327	1555.3	464.23	333.1	11.712	670.1	23.16	61.750	85
90	0.07018	965.30	2.3591	376.97	2659.5	1.1927	7.4781	4.2051	2.0415	1.3340	1552.7	466.98	314.2	11.885	672.8	23.62	60.816	90
95	0.08461	961.89	1.9806	398.02	2667.6	1.2502	7.4150	4.2106	2.0586	1.3355	1549.3	469.66	297.1	12.06	675.2	24.09	59.870	95
99.9743[b]	0.101325	958.37	1.6733	418.99	2675.5	1.3067	7.3544	4.2166	2.0774	1.3371	1545.1	472.24	281.7	12.23	677.2	24.57	58.917	99.9743
100	0.10142	958.35	1.6719	419.10	2675.6	1.3070	7.3541	4.2166	2.0775	1.3371	1545.1	472.26	281.6	12.23	677.2	24.57	58.912	100
105	0.12090	954.71	1.4185	440.21	2683.4	1.3632	7.2951	4.2232	2.0983	1.3390	1540.1	474.77	267.5	12.41	678.9	25.07	57.943	105

4.6 Timetable for Deliverables of ASHRAE RP-1767

Deliverables	Schedule
1. New SI and I-P moist air property tables for the ASHRAE Handbook of Fundamentals, Psychrometrics Chapter	~~6/30/2017~~ 12/3/2017
2. New figures 12 and 13 in the Psychrometrics Chapter of the ASHRAE Handbook of Fundamentals calculated from results of this research	~~6/30/2017~~ 12/3/2017
3. Comparison of new algorithms for transport properties of moist air to former equations	~~6/30/2017~~ 12/3/2017
4. SI and I-P transport properties of water at saturation for the liquid and the gas phase	12/31/2016
5. Update of table for refrigerant 718 (water/steam) in the ASHRAE Handbook of Fundamentals, Chapter 30	12/31/2016
6. Final report documenting all used equations and coefficients	~~12/31/2017~~ 6/30/2018 (decision of TC 1.1 in Long Beach)

5. Conclusions and Outlook

- Saturated water and steam properties done (finished by end of 2016)
- Fortran code for calculating moist air transport properties prepared
  - using latest NIST equations for transport properties of dry air
  - incorporating current IAPWS formulations for water and steam
  - including an improvement of the current mixing model for transport properties of moist air
- New SI tables for the ASHRAE Handbook of Fundamentals, Psychrometrics Chapter were prepared, I-P tables in preparation
- New SI figures 12 and 13 for the ASHRAE Handbook of Fundamentals, Psychrometrics Chapter, I-P figures in preparation
- Preparing the Final Report including all equations and coefficients by the end of June 2018
- Reporting the results of RP-1767 in a track (seminar, …) as an oral presentation at the 2018 ASHRAE Annual Conference in Houston, TX
- Preparing of a research paper for the Journal *Science and Technology for the Built Environment* (former *HVAC&R Research*) by end of September 2018

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