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Large scale test of a novel back-pass non-perforated unglazed solar air collector

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1 **LARGE SCALE TEST OF A NOVEL BACK-PASS NON-PERFORATED**
2 **UNGLAZED SOLAR AIR COLLECTOR.**

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32 **LARGE SCALE TEST OF A NOVEL BACK-PASS NON-PERFORATED**
33 **UNGLAZED SOLAR AIR COLLECTOR**

34

35 **Abstract**

36 This paper describes large scale tests conducted on a novel unglazed solar air collector
37 system. The proposed system, referred to as a back-pass solar collector (BPSC), has on-site
38 installation and aesthetic advantages over conventional unglazed transpired solar collectors
39 (UTSC) as it is fully integrated within a standard insulated wall panel. This paper presents the
40 results obtained from monitoring a BPSC wall panel over one year. Measurements of
41 temperature, wind velocity and solar irradiance were taken at multiple air mass flow rates. It
42 is shown that the length of the collector cavities has a direct impact on the efficiency of the
43 system. It is also shown that beyond a height-to-flow ratio of $0.023 \text{ m}^3/\text{hr}/\text{m}^2$, no additional
44 heat output is obtained by increasing the collector height for the experimental setup in this
45 study, but these numbers would obviously be different if the experimental setup or test
46 environment (e.g. location and climate) change. An equation for predicting the temperature
47 rise of the BPSC is proposed.

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50 **Keywords:** solar air heaters, back pass non-perforated unglazed solar collector, thermal
51 efficiency, and renewable energy.

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64 **Nomenclature**

65	A_o = orifice area (m^2)
66	ΔP = orifice differential pressure (Pa)
67	β = orifice diameter / duct diameter (d/D)
68	C_p = heat of air ($Kj/kg\ ^\circ C$)
69	d = orifice diameter (m)
70	D = duct diameter (m)
71	E_{dir} = Direct radiance incident on tilted surface (W/m^2)
72	E_{dir} = Diffuse radiance incident on tilted surface (W/m^2)
73	E_{ref} = Reflected irradiance incident on tilted surface (W/m^2)
74	E_L = Incident long wave radiation on the collector in W/m^2
75	F_R = Collector efficiency factor
76	f = enhancement factor
77	G_{solar} = Global solar radiance incident on surface (W/m^2)
78	G_{tot} = Total solar radiance incident on surface (W/m^2)
79	M = molar mass ($kg/kmol$)
80	m_{air} = Air flow rate (kg/s)
81	NO = Universal gas constant ($kj/kmol.K$)
82	P_a = atmospheric pressure (kPa)
83	P_s = saturated vapour pressure over water (kPa)
84	P_{sc} = corrected saturated vapour pressure (kPa)
85	P_u = orifice upstream pressure (Pa)
86	P_v = partial vapour pressure (kPa)
87	R = specific gas constant for moist air (kJ/KgK)
88	RH = relative humidity (%)
89	t = temperature ($^\circ C$)
90	t_o = Outlet temperature ($^\circ C$)
91	t_a = Ambient temperature ($^\circ C$)

92 $U_{L=}$ Heat loss coefficient (W/m²K)
93 ε = expansibility factor
94 σ = Stefan-Boltzmann constant (=5.67 x 10⁻⁸ W/m²K⁴)
95 $\tau\alpha$ = Effective transmittance-absorptance factor
96 μ = instantaneous efficiency (%)
97 ν = kinematic viscosity (m² /s)
98 ρ_a = density of moist air (kg/m³)
99 α = flow rate coefficient
100 γ = isentropic exponent for air (~1.4)

101

102 **1. Introduction**

103

104 The operational energy of non-residential buildings accounted for 40% of the European
105 Union's energy consumption and carbon emissions in 2010 [1]. Of this, 50% was used for
106 heating, ventilation and air conditioning services (HVAC). In the UK, the Government target
107 for carbon emissions is to achieve an 80% reduction by 2050 [2]. One of the means of
108 achieving this reduction is through the use of renewable energy systems. However, only 1.8%
109 of operational energy is supplied from renewable energy sources in the UK at present [3].

110 Energy efficiency measures have been included in part L of the UK Building Regulations [4],
111 which are aimed at reducing energy consumption and therefore reducing CO₂ emissions. One
112 of the major challenges for the UK construction industry is to develop more efficient and
113 effective technologies based on renewable sources of energy, such as solar energy.
114 Additionally, effective energy storage systems must be developed to satisfy the energy
115 demands of end users, as and when it is required, because most renewable energy sources are
116 transient in nature.

117 Solar energy can potentially be absorbed and converted by using solar collectors to provide
118 space heating in commercial buildings and in large enclosures, such as warehouses and
119 superstores. Technologies, such as solar air collectors (SACs), can therefore result in the
120 building envelope becoming a producer of energy for space heating [5].

121 SACs are a special type of heat exchangers that absorb incident solar radiation, and convert it
122 to useful thermal energy via a photothermal process (see Fig. 1). In a SAC, the absorber
123 transfers the energy from the solar irradiance to the air flowing through the collector by
124 forced or natural convection, depending on the collector configuration. This heated air inside
125 the collector is then transported as circulating air directly into the building. SACs were first
126 described by Hollick and Peter [6] who used solar radiation to preheat air for ventilation.
127 However, it was in the last three decades that effective solar air collector technologies have
128 been developed [7]. Since then more than one thousand SACs have been installed in over 30
129 countries [8].

130 *Fig.1 Wall integrated solar air collector*

131 SACs can be classified as glazed and unglazed depending on the material of the absorber
132 plate. Glazed SACs recirculate the internal air of the building through a solar air glazed panel
133 in which the air is heated and then directed back into the building. Unglazed SACs consist of
134 a bolt-on dark-coloured metal absorber plate, through which ambient air outside the building
135 is passed, before being drawn into the building to provide pre-heated fresh air for both
136 ventilation and heating purposes. The most common applications of this technology are the
137 transpired solar air collectors (TSC).

138 A TSC consists of an unglazed solar air system with a perforated absorber layer. Unglazed
139 transpired solar air collectors (UTSC) use solar energy to heat the absorber surface, which
140 transmits thermal energy to the ambient air (Fig. 2). The absorber surface is generally a metal

141 sheet (usually steel or aluminium), which can be attached to the building facade. The contact
142 surface between the metal skin and air is increased by drawing air through multiple small
143 perforations in the solar absorbing sheet into the cavity between the skin and facade. The
144 heated air is then drawn into the building to provide space heating.

145 *Fig. 2 Unglazed transpired solar collectors (UTSC)*

146 A number of studies on the layout of UTSC perforations in the solar absorbing sheet have
147 been conducted to evaluate heat transfer, efficiency, airflow distribution, and pressure drop.
148 Leon and Kumar [9] developed a mathematical model to predict the thermal efficiency of a
149 “bolt-on” UTSC over a range of different operating conditions. It was reported that the main
150 factors affecting the heat exchanger effectiveness and air temperature rise ($\Delta T^{\circ}\text{C}$) were: (i) air
151 flow rate (ms^{-1}), (ii) solar radiation (Wm^{-2}), and (iii) solar absorptivity (α) by the collector.
152 Efficiencies of up to 65% were reported in this work. Gunnewiek [10] studied the flow
153 distribution in UTSC using CFD simulations. Gawlik [11] studied the performance of low-
154 conductivity unglazed, transpired solar collectors numerically and experimentally.

155 As an alternative to the UTSC, Othman [12] developed a “bolt-on” prototype solar drying
156 system using back-pass solar collector (BPSC) technology and found that the controlled air
157 flow could maintain the output temperature from the collector constant even if the solar
158 radiation intensity varies to certain degree.

159 The integration of a BPSC into an insulated wall panel (see Fig. 3) has both on-site
160 installation and aesthetic advantages over conventional UTSC in that it is fully integrated
161 within a standard insulated wall panel, avoiding the negative impact of the perforations on the
162 building’s appearance, and matching aesthetically the rest of the building’s envelope.
163 However, to the best knowledge of the authors, no large scale study on BPSC systems,

164 similar to that on an UTSC, has been conducted. This paper presents the results of a study of
165 the thermal efficiency of such an SAC system.

166 *Fig.3 Back pass non-perforated solar collectors (BPSC)*

167 For the BPSC described in this paper, an existing composite panel consisting of five crowns
168 was modified (see Fig. 4) in order to integrate the BPSC through which fresh external air is
169 taken from the base of the profiled voids under the crowns of the panel. By utilizing the outer
170 steel skin of the panel as a solar collector, incident solar radiation is absorbed, resulting in an
171 increased temperature of the air within the crown (see Fig.5).

172 Existing studies have indicated that the BPSC system may result in savings of up to 20% of
173 the energy required for heating, with a pay-back period of 2.5 years [13].

174 *Fig.4 Photograph of BPSC*

175 *Fig.5 Drawing of the test BPSC system*

176 **2. Experimental setup and instrumentation**

177

178 A South facing test rig [14] was constructed at Kingspan R&D facilities in Kingscourt,
179 Ireland (Fig. 6). Kingscourt has a longitude of 6.8 degrees west and a latitude of 53 degrees
180 North. The BPSC dimensions of the test rig are 7.04 m x 4 m. The rear plenum was
181 connected a fan outlet using ducts which were insulated.

182 *Fig.6 Photograph of BPSC test-rig*

183 **2.1. Global solar radiation measurement**

184 The global solar radiation was measured using two Kipp and Zonen CMP11 pyranometers. A
185 Kipp and Zonen CM121 shadow ring was used to shade one of the pyranometers, allowing
186 the ground-reflected solar radiation to be measured. The unshaded pyranometer included a
187 white body shading cone to minimise body heating. The pyranometers were installed to one
188 side of the test panel at around its mid-height. Both were installed vertically and aligned with
189 the test panel. None of the sensors or mountings shaded the panel. The CM121 shadow ring
190 was used with the pyranometer also in the vertical position, aligned with the test panel. The
191 shadow ring was periodically adjusted to ensure the sensor remained shaded through the test
192 period.

193 The long wave radiation from the sky was also measured by a Kipp and Zonen CGR4
194 pyrgeometer. This was installed in the vertical plane alongside the test panel at approximately
195 mid-height. A body shading cone was also used. The integral thermistor output was used for
196 the calculation of net long wave radiation.

197 **2.2. Air temperature measurement**

198 The air temperature was measured using class 1/10th DIN, 4-wire PT100 probes at 5 air inlets
199 equally spaced across the base of the panel, and at 5 positions arranged in an array in the
200 collector chamber or plenum immediately before the air outlet. A single sensor suspended at
201 approximately the mid-height of and behind the panel was used to measure the ambient
202 temperature. All the exposed air temperature sensors (at inlets and behind the panel) were
203 housed in double skin radiation shields to minimise effects of incident solar radiation. These
204 shields had a tube-in-tube construction. The cylindrical body of the outer tube was wrapped
205 by reflective foil to reflect solar radiation. The ends of the tubes were open and ventilation

206 holes were drilled in both tubes prior to assembly. These holes were offset between the inner
207 and outer tubes to prevent direct ingress of radiation at any angle. Figure 7 shows the air
208 temperature sensor shield at the air inlets. Four channel cavities of the BPSC collector were
209 instrumented with one air temperature sensor each at a height of 3.5 m above the air inlets to
210 measure the air temperature there. All holes for cable passage were well sealed with duct
211 sealant and visually inspected. All sensors were checked using a PT100 simulator across the
212 range of expected operation and corrected for any offsets.

213

214 *Fig.7 Air temperature sensor shield and positioning at air inlet point of BPSC*

215

216 **2.3. Air flow measurements**

217 Air flow was measured via two ISO 5167 [15] orifice plates with corner taps, mounted in
218 separate parallel duct sections downstream from the panel plenum. Flow rate could therefore
219 be calculated using the methods in ISO 5801[16], by measuring differential pressure across
220 the plates as well as the variables such relative humidity, atmospheric pressure and duct air
221 temperature. Only one orifice plate was used at a time. The use of two plates enabled a greater
222 flow range to be tested whilst ensuring that the pressure difference did not either drop too low
223 to enable accurate measurements to be taken, or for the overall pressure drop to be too high
224 for the driving fan. The two orifice plates were designed and manufactured by Poddymeter,
225 and the specification was 200 Pa differential pressure at 500 m³/hr (for an orifice diameter of
226 0.12532 m) and 900 Pa at 2200 m³/hr (for an orifice diameter of 0.17264 m). The installation
227 was checked for correct flow directions on the plates and that the plates were suitably sealed
228 with gaskets on the flange faces. The housing ducts were 250 mm diameter and the straight

229 sections joining the plates were greater than 3 m upstream and 1.5 m downstream, thus
230 achieving greater than 12 and 6 duct diameters of straight section, respectively (see Fig.8).

231 *Fig.8 Orifice plates with corner taps, mounted in separate parallel duct sections*

232 Differential pressure across the orifice plates was measured using Sontay PA267 transmitters
233 (with an optional higher accuracy specification), in 0 - 500 Pa or 0 - 1000 Pa range depending
234 on the orifice plate and flow rate used. Atmospheric pressure was measured using a Pi605
235 atmospheric pressure transmitter from Omni Instruments, with the higher accuracy
236 specification option (< 0.1 % combined error). Relative humidity inside the duct was
237 measured by a Rotronic HC2-S transmitter, with the head completely inserted into the duct at
238 the same location as the temperature sensor array. Calibration was performed by Industrial
239 Temperature Sensors Ltd, and was within the specification of the manufacturer in the region
240 of interest, typically 20 – 50 % RH after heating.

241 **2.4. Winds peed measurements**

Commented [BS1]: Wind speed measurements

242 Wind speed was measured at either side of the panel at mid-height by Vector Instruments
243 A100 series anemometers with a reduced full-scale range of 0 - 25.74 m/s. These were
244 mounted with leading / trailing edge boards extending from the panel edge behind the
245 anemometers to give a continuous surface as per the requirements of EN12975 [17].

246 **3. Data collection**

247 Test data were collected over a one year period, during which a total of 250 tests were
248 conducted, mostly in conditions with relatively high solar radiation (400 to 900 W/m²). A
249 feature of the test is the variation in energy collection under apparently similar conditions.

250 The general principle for the measurements was to record a stable panel pre-conditioning
251 period of 15 minutes followed by a steady state data collection period for performance

252 evaluation of 10 minutes [18]. During these periods, the parameters of solar and long wave
253 irradiance, air temperature, fluid mass flow rate, collector fluid inlet temperature and
254 surrounding air speed were within specified tolerances in EN12975-2:2006. Other parameters
255 were not necessarily within the specified ranges but they were beyond our control. Those data
256 outside the specified ranges were The BPSC fluid inlet temperature in this configuration was
257 the same as the ambient air temperature. The air mass flow was generally within tolerance
258 although for individual readings, there were temporary deviations outside of the $\pm 1\%$
259 average. In general, the average over the measurement period was stable with almost no
260 drifting.

261 **3.1. Measurement processing**

262 The global solar radiation (G_{solar}) on a tilted surface consists of the direct irradiance (E_{dir}),
263 diffuse irradiance (E_{diff}) and the reflected radiation or albedo (E_{ref}):

$$264 \quad G_{solar} = E_{dir} + E_{diff} + E_{ref} \quad (1)$$

265 The unshaded CMP11 reading provides the direct solar radiation on the panel. The CGR4
266 reading provides the diffuse or incident long wave radiation from the sky. The CMP11
267 mounted with the shadow ring provides the ground-reflected solar radiation. However, the
268 global solar radiance per m^2 area was calculated in accordance to EN12975- 2 [17].

269 For subsequent solar radiation to collected heat conversion efficiencies, the total radiation
270 available for collection was determined by the useful area of the panel. This is defined as the
271 proportion of the panel where air circulates through the channels, including the “finned”
272 elements between the channels. It does not include the panel area above the top of the
273 connecting holes through the panel insulation to the plenum, since the air here is stagnant.
274 For the test BPSC, the effective area was taken as 4 m x 6.5 m. However, the 0.5 m above the
275 plenum holes were considered ineffective. The effective area of the test panel was therefore
276 26 m².

277 **3.2. Air inlet and outlet temperatures**

278 The five inlet temperatures were averaged to give an air inlet reference temperature: their
279 variation was small, generally within 0.5 °C. The readings of the five outlet sensors were also
280 averaged. They were used to determine the reference temperature difference in the heat
281 output calculations.

282 **3.3. Air flow rate**

283 The calculation of the airflow through the orifice plate was conducted in accordance with ISO
284 5801 [16]. The method required the following measured parameters:

- 285 • Differential pressure across the plate
- 286 • In-duct relative humidity
- 287 • In-duct air temperature
- 288 • Atmospheric pressure

289 Specific heat capacity for moist air was calculated as a function of the air temperature and
290 moisture content, with the reference temperature being the average of the panel inlet and
291 outlet temperatures [19].

292 **4. Data analysis**

293

294 The amount of heat delivered by the BPSC is given by:

295

296
$$Q = m_{air} C_p (t_o - t_a) \quad (2)$$

297

298 where C_p is the specific heat of air (kJ/kg °C), m_{air} is the mass flow rate through the BPSC

299 (kg/s), t_o is the outlet air temperature (°C), t_a is the inlet (ambient) air temperature (°C).

300 The instantaneous efficiency of the BPSC is defined by the Hottel-Whillier-Bliss equation
301 [20]

303

302
$$\mu = \frac{Q}{AG_{tot}} = F_R \tau \alpha - \frac{F_R U_L (t_o - t_a)}{G_{tot}} \quad (3)$$

304

305 where A is the effective area of the collector (m²), G_{tot} the total solar irradiance on the
306 collector surface (W/m²), F_R the heat removal factor, $\tau \alpha$ the effective transmittance-
307 absorptance product which depends on the angle of solar incidence, and U_L the overall heat
308 loss coefficient (W/m²K). In Equation (3) the effective transmittance-absorptance product,
309 $F_R \tau \alpha$, and the overall heat transfer coefficient for losses from the collector $F_R U_L$ are constant
310 over the entire collector plane.

311

312 The total solar radiation is dependent on the global solar radiation and the ratio ε/α based on
313 the ambient temperature as follows:

314

315
$$G_{tot} = G_{solar} \pm (\varepsilon/\alpha)(E_L - \sigma t_a^4) \quad (4)$$

316

317 where σ is the Stefan-Boltzmann constant ($=5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$), ϵ is the emittance of the
318 collector surface, α is the solar absorptance of the collector surface, E_L in W/m^2 is the
319 incident long wave radiation mainly from the sky but also from terrestrial surroundings of the
320 collector, and t_{amb} is the ambient temperature.

321 The rise of air temperature in the collector varies with the distance from the air inlet, which is
322 dependent on (i) the absorptivity of the BPSC, (ii) the heat transfer coefficient between the
323 collector surface and the environment, and hence (iii) the local wind speed, (iv) the heat
324 transfer coefficient between the BPSC surface and the air in the collector, and thus potentially
325 on (v) flow rate and (vi) the back losses from the collector to the environment behind it,
326 usually the building interior. The basic model in Fig. 9 shows that the highest efficiency
327 between 35% and 39% was obtained with flow rates between 90 and 120 $\text{m}^3/\text{hr}/\text{m}^2$ at inlet
328 temperatures between $-6 \text{ }^\circ\text{C}$ and $8 \text{ }^\circ\text{C}$. For a given total air flow, defined by the room
329 ventilation needs, splitting the flow between a series of low collectors has two effects: a low
330 collector is more efficient but has a reduced flow rate per collector.

331 *Fig.9 Effect of air flow rate on efficiency*

332 **4.1.1. Effect of wind speed on temperature rise**

333 Figure 10 shows that the temperature rise per unit of solar radiation is not affected by the
334 wind speed for the tested BPSC within the test range of 0.3 and 4 m/s.

335 *Fig.10 Effect of wind speed on temperature rise per unit radiation*

336 **4.1.2. Effect of flow rate on temperature rise per unit of solar radiation**

337 The majority of the tests were conducted with a flow rate between 40 and 140 $\text{m}^3/\text{hr}/\text{m}^2$.
338 Within this range, there is a consistent linear relationship where an increase of the flow rate
339 reduces the temperature rise.

340 *Fig.11 Effect of air flow rate on temperature rise*

341 **4.1.3. Stabilised temperature rise**

342 Based on the results on the effect of air flow rate on efficiency, Fig. 12 presents the results of
343 temperature rise for different levels of solar radiation at airflow rates between 90 and 120
344 $\text{m}^3/\text{hr}/\text{m}^2$ at inlet temperatures between $-6\text{ }^\circ\text{C}$ and $8\text{ }^\circ\text{C}$.

345 *Fig.12 Effect of solar radiation on temperature rise*

346 The results for temperature rise per unit radiation (Fig.13) show very little variation with flow
347 rate, suggesting that the combination of flow rate and height is sufficient for the observed
348 temperature increases close to saturation value. This relationship can be used to estimate the
349 exit air temperature as a function of flow rate, radiation level and height, and thus to estimate
350 how the performance of the BPSC would vary with height. Qualitatively, if the collector is
351 relatively large compared to the characteristic length, the exit temperature will be close to the
352 saturation temperature. However, if the height is low, the exit temperature will be lower,
353 although the efficiency will be higher.

354 *Fig.13 Variation of temperature rise per unit radiation against flow rate*

355 The results show that the temperature increases with the height/flow ratio up to a certain
356 point, after that the temperature is constant and the collector height is effectively infinite.

357 **5. Discussion of results**

358 The BPSC on the south elevation was tested in detail to characterise the performance of the
359 panel and develop an empirical model to be used to estimate the panel temperature discharge
360 and efficiencies.

361 The exit temperature from the BPSC is a function of solar radiation, height of the collector
362 and air flow rate in the collector:

$$363 \quad T_{out} = f(G_{tot}, h, m_{air}) \quad (5)$$

364 The performance of the BPSC is determined by the temperature rise of the exit temperature
365 above to ambient temperature. From the experimental data of the collector, the exit
366 temperature, relative to ambient, in terms of rise per unit incident radiation can be calculated,
367 which defines the basic thermal model of the collector:

$$368 \quad \Delta T_{rad} = \Delta T'_{rad} \left(1 - e^{-\frac{hE}{m_{air}}} \right) \quad (6)$$

369 Where E is the air flow rate coefficient, m_{air} is the air flow rate ratio

370 At the maximum height or zero flow rate: $\Delta T_{rad} = \Delta T'_{rad}$

371 The useful thermal energy delivered to the building is simply calculated by:

$$372 \quad Q = m_{air} \rho C_p \Delta T_{rad} G_{tot} \quad (7)$$

373 Where ρ is the density of the air, 1.22 kg/m^3 , G_{tot} is given by equation (16).

374

375 ΔT_s can be estimated from these values by using the data point from the highest value of the
376 height/flow ratio, in this case 0.0134 (at a ratio of 0.223). Re-arranging equation [6], the
377 following equation is proposed:

$$378 \quad \ln \left(\frac{1 - \Delta T}{\Delta T_s} \right) = E(h/m_{air}) \quad (8)$$

379 The estimation of E is $-8.07/0.223 = -36.19$. This illustrates that beyond a certain height (h) to
380 air flow rate (m_{air}) ratio, no additional heat is collected.

381 **6. Conclusions**

382 A novel wall-integrated and unglazed solar air collector has been developed. A large scale rig
383 having a panel surface area of 26m² was tested to determine the physical behaviour of the
384 back-pass non-transpired solar collectors (BPSC) prototype, and to identify the governing
385 factors in the collector performance.

386 It was found that wind speeds of up to 4 m/s across the collector metal plate had no impact on
387 the performance of BPSC. The results also showed that the estimation of the exit air
388 temperature of the solar air collector would depend on the intensity of the solar radiation, air
389 flow rate through the collector crowns and the solar collector height ($T_{out} = f(G_{tot}, h, m_{air})$).
390 For the panels monitored, it was shown that beyond a 0.023 m³/hr/m² height-to-flow ratio,
391 there was no additional heat collection. It was also observed that the temperature increases
392 with the height/flow ratio up to a certain height where there is no additional heat collection.
393 However, efficiencies up to 39% can be achieved with a combination of collector lengths and
394 effective air flow rates in the range of 90-120 m³/hr/m².

395

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399

400

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445 **Appendix A. Mass flowrate of air**

446

447 Mass flowrate of air [17]:

$$448 \quad m_{air} = \alpha \varepsilon \pi \frac{d^2}{4} \sqrt{2 \rho_u \Delta p} \quad (1A)$$

449 Where α is the flow rate coefficient [14]:

$$450 \quad \alpha = (1 - \beta^4)^{-0.5} [0.5959 + 0.0312 \beta^{2.1} - 0.184 \beta^8 + 0.0029 \beta^{2.5} (\frac{10^6}{R_D})^{0.75}] \quad (2A)$$

451 The Reynolds number [14] is:

$$452 \quad R_D = \frac{\alpha \varepsilon \beta d}{\nu} \sqrt{\frac{2 \Delta p}{\rho_u}} \quad (3A)$$

453 The expansibility factor [14] is:

$$454 \quad \varepsilon = 1 - (0.41 + 0.35 \beta^4) \frac{\Delta p}{k p_u} \quad (4A)$$

455 The kinematic viscosity [14] is:

$$456 \quad \nu = \frac{(17.1 + 0.0048 t_{out})^{-6}}{\rho_u} \quad (5A)$$

457 The saturated vapour pressure [18]:

$$458 \quad P_s = 10^{(30.590521 - 8.2 \log(\theta + 273.15) + 0.0024804(\theta + 273.15) - (\frac{3142.31}{\theta + 273.15}))} \quad (6A)$$

459 The enhanced factor [19]:

$$460 \quad f = 1 + A + P_a [B + C (t_{out} + D + EP)^2] \quad (7A)$$

461

462 The partial vapour pressure [18]:

$$463 \quad P_v = \left(\frac{R_H}{100}\right)\rho_s \quad (8A)$$

464 The Molar ratio [19]:

$$465 \quad \alpha_i = \frac{P_v}{P_a} \quad (9A)$$

466 Molar mass moist air [19]:

$$467 \quad \alpha_a = \left(\frac{P_v}{P_a}\mu_{wat}\right) + \left(1 - \frac{P_v}{P_a}\right)\mu_{air} \quad (10A)$$

468 Equivalent gas constant [19]:

$$469 \quad R = \frac{\bar{R}}{\alpha_a} \quad (11A)$$

470 Density moist air [19]:

$$471 \quad \rho_u = \frac{P_a}{R(t_{out}+273.15)} \quad (12A)$$