Correlating bekk Air Resistance with Bendtsen Air Permeability Measurements

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ABSTRACT

The Bekk smoothness tester can be changed to measure air resistance by altering the clamps and boundary pressure conditions. However, this instrument configuration does not correspond to the well known series of ISO standards that cover such measurements. Nevertheless, some companies still use Bekk to measure 'porosity'. This is not a problem until they transmit data to a third party, where the lack of published correlation between Bekk and other standardised equipment means such data are difficult to interpret. This article bridges the gap, providing equations derived from both theory and experimentation that allow Bekk data to be expressed in terms of Bendtsen air permeability.

Introduction

The rate at which air can be forced through a paper sheet gives information on, among other things, the degree of fibrillation of the fibres, their compaction and the presence of coating layers or certain filler types. It is one of the easiest and quickest tests that are routinely applied to paper, and as a rapid diagnostic it has much to commend it, given certain caveats. Although such tests are commonly described as measuring porosity (the ratio of voids to solid volume of a material) they actually measure permeance - the volume of interconnected paths by which air can pass through a sheet (assuming leakage across surfaces is neglected). The tests can further be sub-divided according to whether the value increases with the number of voids, or decreases: the former measures flow volume per unit time (air permeability) while the latter tends to have units of time per unit flow volume (air resistance). So Bendtsen, Potts, Sheffield and Schopper measure permeability; Gurley resistance.

These tests are covered by a connected series of ISO standards (1) which also contain a series of equations by which one measurement can be converted to another. (The ability to do this relatively simple transformation is the basis by which some instrument manufacturers can produce universal air permeability testers, where the numbers from a single test can be re-displayed as if they were made on another apparatus at the touch of a button.) The two main requirements for inclusion in such standards is that the surfaces should be adequately sealed to prevent air leakage, and the pressure drop between the two surfaces of the sheet under examination should be reasonably constant throughout the test, since the rate of flow is proportional to this pressure drop and the area over which the test is made.

This article describes measurements made with another common air-flow apparatus, the Bekk smoothness tester, where a simple alteration of the clamps changes it to an air resistance tester. It is not covered by the standards described above because the pressure drop across the two surfaces changes markedly during the test (from 50.66 to 29.33kPa). Indeed, only one nominal standard referring to its use has been found (2). However this does not preclude some companies from using it as an air resistance tester, since it still produces numbers that change as the properties of the test specimen are altered. Use of this apparatus only becomes a problem when the data are transmitted to a third party, maybe as a specification, where the lack of a published correlation means it cannot be understood in terms of other more common apparatus.

To date only two publications mentioning correlation of Bekk air resistance with other instruments have been found. That by Tollenaar and van Royen (3) produced an unsatisfactory equation relating it to Schopper, where derived values were up to 50% inaccurate. Their work also produced an interesting artefact; performing the Bekk test repeatedly on a sample has a major effect on the paper, tending to decrease the measured permeability with time, which suggests the rather high pressures exerted during this test are capable of effecting structural changes to the paper. Meanwhile, a conference presentation by Paavola et al (4) described use of an online porosity sensor that could be made to read like a number of different laboratory apparatus, including Bekk and Bendtsen. However, no correlation equations were provided, nor were the algorithms devised for each instrument published. Also, this work reported that Bekk measures time to pull 100ml of air through a sheet, when actually the pressure differential accounts for only 80ml of air (5).

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Results and Discussion

Figure 1 shows a surprisingly good correlation between the Bekk air resistance (Bk) and Bendtsen air permeability (Be) measurements. Although for a number of reasons the Bekk is a suspect instrument to use for this purpose, reported data at least show it can produce a reasonable degree of discrimination. The correlation equation derived from this relationship is shown on the graph, and can be expressed in the following linear form:

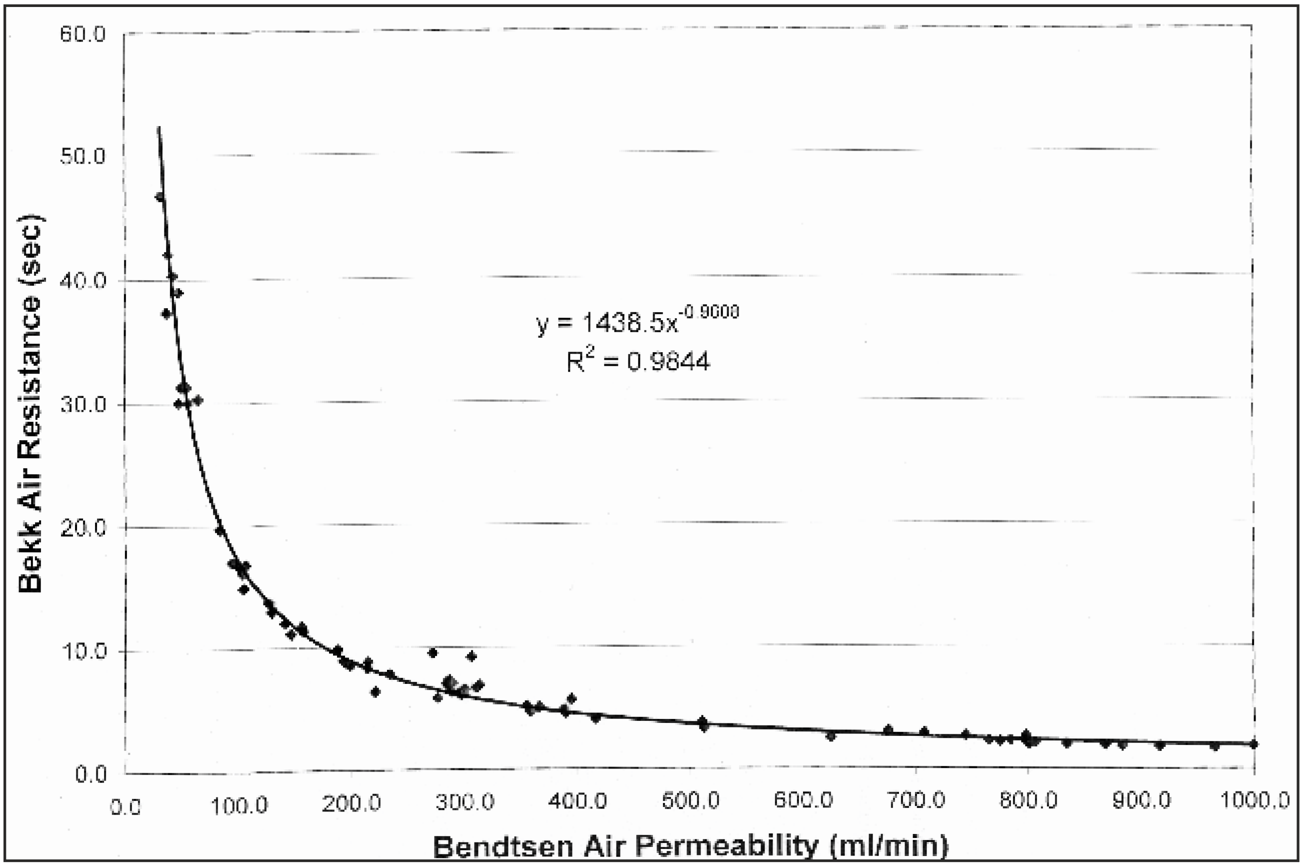
(1) $\log(Bk) = 3.16 - 0.9608\log(Be)$

ISO 5636-1 contains the following equation which allows different air leak apparatus that conform to the standard to be equated (where P = air permeance (µm/Pas); V = volume of air passing through test area (ml); A = test area (m^2); Δp = pressure difference (kPa); t = test duration (s)):

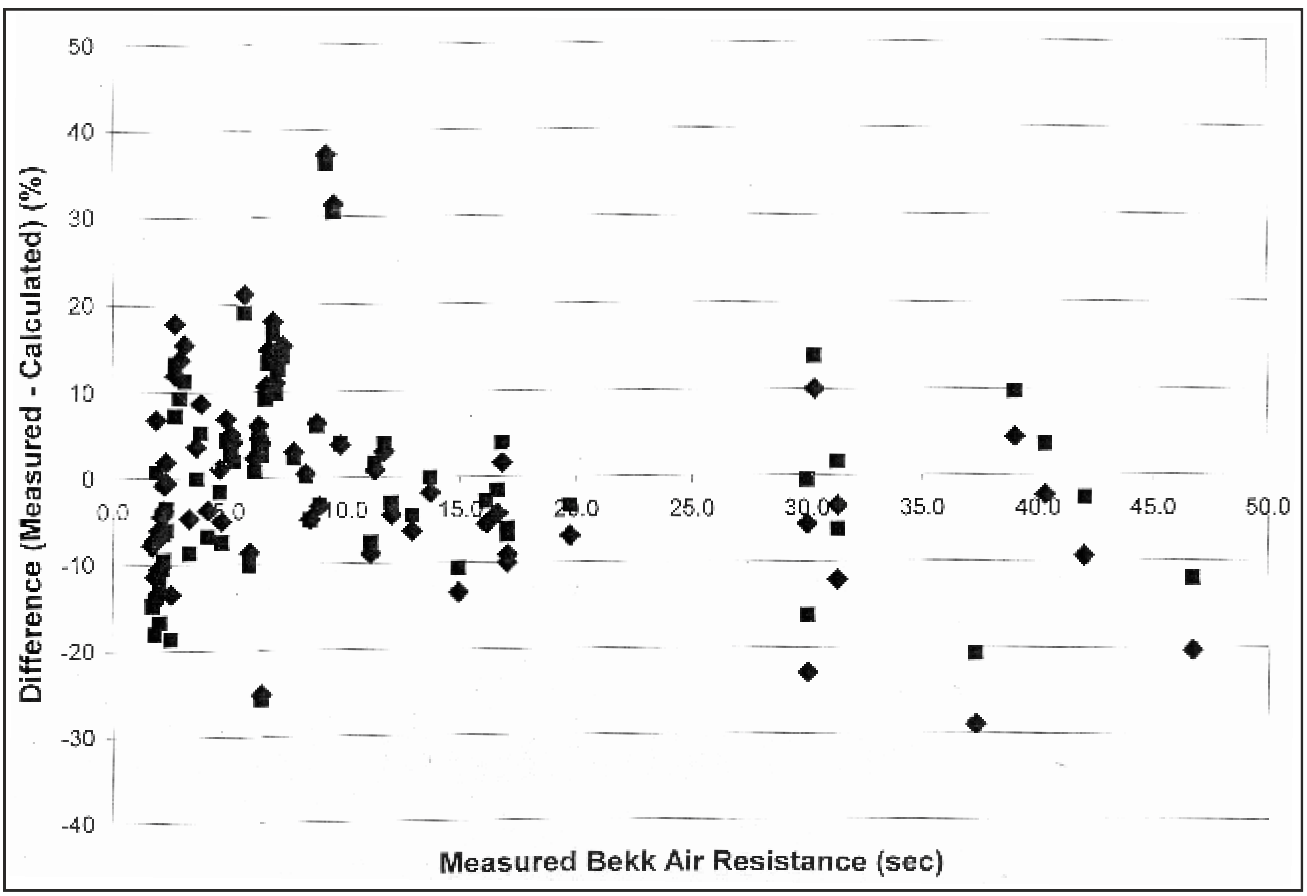
(2) $P = V / (1000\, A\, \Delta p\, t)$

Substituting the relevant measurement parameters into this equation yields:

(3) $P_{(Be)} = 0.0113q$



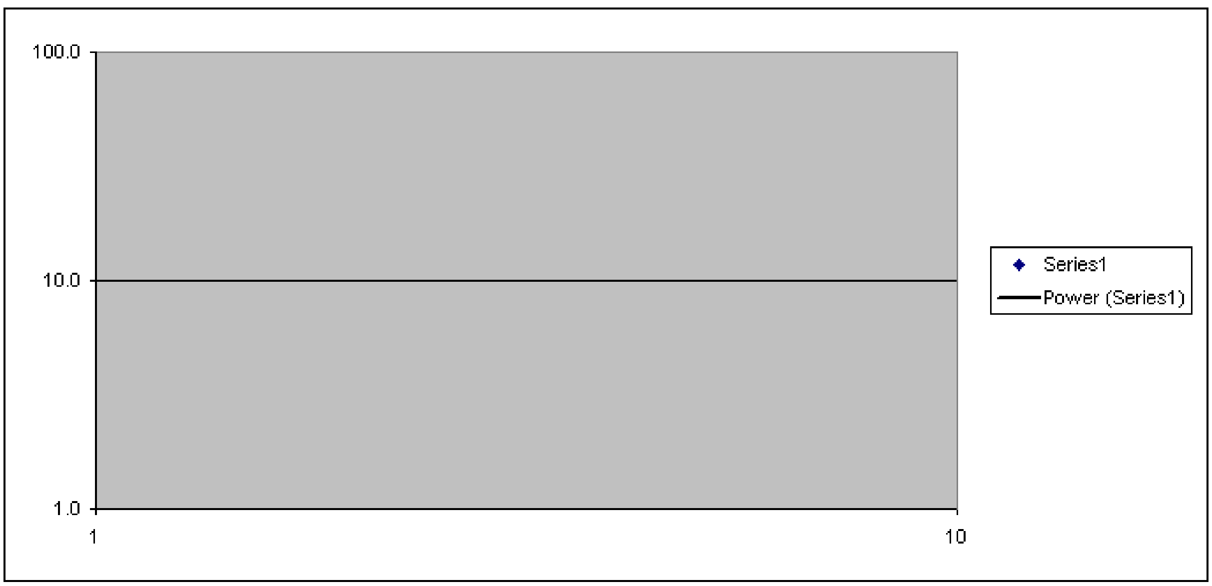
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Bekk Air Resistance (sec)
y = 1438.5x^-0.9000
R^2 = 0.9844
0.0 100.0 200.0 300.0 400.0 500.0 600.0 700.0 800.0 900.0 1000.0
Bendtsen Air Permeability (ml/min)



50
40
30
20
10
0
-10
-20
-30
-40
Difference (Measured - Calculated) (%)
0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0
Measured Bekk Air Resistance (sec)

	ORIGINAL MEASURED DATA		CALCULATIONS USING BENDTSEN - Theory			CALCULATIONS USING BENDTSEN - Practice		
Sheet	Bendtsen	Bekk	Bekk	Bekk	Percent	Bekk	Bekk	Percent
	ml/min	sec	calc from Bendtsen	Delta (bk-be)	Difference	calc from Bendtsen	Delta (bk-be)	Difference
1815m	31.5	46.7	56.2	-9.5	-20	52.3	-5.6	-12
1815u	36.8	37.3	48.1	-10.8	-29	45.0	-7.7	-21
1815v	38.5	42.0	46.0	-4.0	-9	43.1	-1.1	-3
1815p	42.9	40.3	41.3	-1.0	-2	38.9	1.4	4
1815aa	47.5	39.0	37.3	1.7	4	35.2	3.8	10
1815t	48.0	30.0	36.9	-6.9	-23	34.9	-4.9	-16
1815c	50.4	31.3	35.1	-3.8	-12	33.3	-2.0	-6
1815n	54.6	31.3	32.4	-1.1	-4	30.8	0.5	2
1815q	55.8	30.0	31.7	-1.7	-6	30.2	-0.2	-1
1815b	64.9	30.3	27.3	3.0	10	26.1	4.2	14
34	84.0	19.7	21.1	-1.4	-7	20.4	-0.7	-3
42	94.7	17.0	18.7	-1.7	-10	18.2	-1.2	-7
41	95.4	17.0	18.6	-1.6	-9	18.0	-1.0	-6
16	102.2	16.6	17.3	-0.7	-4	16.9	-0.3	-2
33	104.2	16.1	17.0	-0.9	-6	16.6	-0.5	-3
17	104.7	14.9	16.9	-2.0	-13	16.5	-1.6	-11
40	107.0	16.8	16.5	0.3	2	16.1	0.7	4
15	126.8	13.7	14.0	-0.3	-2	13.7	0.0	0
40410m	129.0	12.9	13.7	-0.8	-6	13.5	-0.6	-5
1816d	141.2	12.0	12.5	-0.5	-4	12.4	-0.4	-3
56	146.4	11.1	12.1	-1.0	-9	11.9	-0.8	-8
58	155.8	11.7	11.4	0.3	3	11.3	0.4	4
57	157.8	11.3	11.2	0.1	1	11.1	0.2	2
51	187.6	9.8	9.4	0.4	4	9.4	0.4	4
30	192.4	8.9	9.2	-0.3	-3	9.2	-0.3	-3
29	198.4	8.5	8.9	-0.4	-5	8.9	-0.4	-5
50	214.2	8.3	8.3	0.0	0	8.3	0.0	0
52	214.7	8.8	8.2	0.6	6	8.3	0.5	6
32	220.9	6.4	8.0	-1.6	-25	8.0	-1.6	-26
31	233.8	7.8	7.6	0.2	3	7.6	0.2	2
21	271.4	9.5	6.5	3.0	31	6.6	2.9	31
8	276.0	5.9	6.4	-0.5	-9	6.5	-0.6	-10
3	284.0	7.0	6.2	0.8	11	6.3	0.7	10
6	286.0	7.3	6.2	1.1	15	6.3	1.0	14
47	287.9	6.4	6.1	0.3	4	6.2	0.2	3
40410l	289.0	7.1	6.1	1.0	14	6.2	0.9	12
48	294.5	6.3	6.0	0.3	5	6.1	0.2	3
7	297.0	6.1	6.0	0.1	2	6.1	0.0	1
49	299.0	6.3	5.9	0.4	6	6.0	0.3	5
40410i	300.0	6.6	5.9	0.7	11	6.0	0.6	9
22	305.9	9.2	5.8	3.4	37	5.9	3.3	36
40410j	310.0	6.7	5.7	1.0	15	5.8	0.9	13
40410k	313.0	6.9	5.7	1.2	18	5.8	1.1	17
53	355.2	5.2	5.0	0.2	4	5.1	0.1	2
55	358.5	4.7	4.9	-0.2	-5	5.1	-0.4	-8
54	365.6	5.1	4.8	0.3	5	5.0	0.1	3
5	388.0	4.9	4.6	0.3	7	4.7	0.2	4
2	389.0	4.6	4.5	0.1	1	4.7	-0.1	-2
40410h	394.0	5.7	4.5	1.2	21	4.6	1.1	19

40410f	416.0	4.1	4.3	-0.2	-4	4.4	-0.3	-7
1	510.0	3.6	3.5	0.1	4	3.6	0.0	0
4	510.0	3.8	3.5	0.3	9	3.6	0.2	5
40410d	512.0	3.3	3.5	-0.2	-5	3.6	-0.3	-9
40410c	624.0	2.5	2.8	-0.3	-13	3.0	-0.5	-19
14	675.0	3.1	2.6	0.5	15	2.8	0.3	11
23	707.3	2.9	2.5	0.4	14	2.6	0.3	9
13	744.0	2.7	2.4	0.3	12	2.5	0.2	7
40410b	765.0	2.3	2.3	0.0	-1	2.4	-0.1	-6
40410g	775.0	2.2	2.3	-0.1	-4	2.4	-0.2	-10
24	783.9	2.3	2.3	0.0	2	2.4	-0.1	-4
59	797.6	2.2	2.2	0.0	-1	2.3	-0.1	-7
12	798.0	2.7	2.2	0.5	18	2.3	0.4	13
61	798.3	2.2	2.2	0.0	-1	2.3	-0.1	-6
10	801.0	2.0	2.2	-0.2	-10	2.3	-0.3	-17
60	806.4	2.1	2.2	-0.1	-5	2.3	-0.2	-10
11	834.0	2.0	2.1	-0.1	-6	2.2	-0.2	-12
40410e	868.0	1.9	2.0	-0.1	-7	2.2	-0.3	-14
9	883.0	1.8	2.0	-0.2	-11	2.1	-0.3	-18
27	916.2	1.8	1.9	-0.1	-7	2.1	-0.3	-14
40410a	965.0	1.7	1.8	-0.1	-8	2.0	-0.3	-15
28	999.2	1.9	1.8	0.1	7	1.9	0.0	1



(where A = 0.001; Δp = 1.47; q = volumetric flow in ml/min)

(4) $P_{(Bk)} = 20 / t$
(where V = 80; A = 0.0001; Δp = 40 (mid-point between boundary pressure values))

Balancing these two equalities yields the following theoretical correlation equation:

(5) $\log(Bk) = 3.25 \ \log(Be)$

Analysis of Bekk values derived from Bendtsen data using equations (1) and (5) show errors relative to Bekk data produced by direct measurement. However, data in Figure 2 suggest there is little to choose between either correlation equation, with the majority of calculated values being within ±20% of the measured Bekk value derived from experimentation.

Finally, data in Figure 2 also show the relative difference between values calculated using either equation increases with increasing air resistance, with values produced using the theoretical equation (5) being up to 8% higher than those resulting from the practical equation (1). It is suggested this difference is probably caused by air leakage across the surface of clamped papers, which would make the time values derived from experimentation lower than would be anticipated by theory. (Adequate sealing of surfaces on the Bekk is notoriously difficult.)

Conclusions

Although the Bekk instrument falls outside the strict requirements for inclusion in the linked series of ISO standards for measurement of air permeance, a good relationship has been found with an ISO accredited instrument: Bendtsen.
The relationship is similar whether derived from theory or practice, and is better than that published previously, with the percentage error between measured and derived values being

mainly within ± 20%. However this is still higher than would be expected between other air leak apparatus covered by ISO standards, and as such results derived from use of either correlation equation should be considered as 'ball-park' rather than absolute.

Experimental

Bekk and Bendtsen measurements were made using the respective Messmer Büchel apparatus according to the manufacturer's instructions. In the case of the Bekk instrument this involved replacing the top rubber-trimmed flat clamping plate with one having a void measuring 1cm^2 in the centre; replacing the standard smooth metal plug in the centre of the bottom glass plate with a grooved version; and increasing the clamping pressure. The materials tested included fine writing papers; various carbonless qualities; copier; uncoated thin opaque; airmail paper; décor; and fine text and cover grades. Papers were chosen that fell within the range for Bendtsen measurements covered by ISO 5636-3 (ie. 30-1300ml/min). Comparative tests were made on the same area of each paper sheet, in a conditioned laboratory at 23°C and 50% RH.

References

1. Determination of Air Permeance (medium range): ISO5636-1:1984 (General); ISO5636-2:1984 (Schopper); ISO5636-3:1992 (Bendtsen); ISO5636-4:1986 (Sheffield); ISO5636-5:2003 (Gurley).
2. Central Laboratory of the Research Institute of the Finnish Pulp and Paper Industries, published in 1942 and repeated in 1950.
3. Tollenaar, D. and van Royen, A.H.H., Das Papier, Vol.11, pp.562-566, (1957).
4. Paavola, A.N., Garnett, B.C., Steel, T.H and Hird, A., 59th Appita Annual Conference, Vol.1, pp.211-215 (2005).
5. Determination of Smoothness (Bekk method) ISO5627:1995.

Figure 2 Graph showing the percentage difference obtained when using Bendtsen measurements to calculate Bekk data, against actual measured Bekk values. (Derived values: squares show data from theoretical equation (5); diamonds show that from practical equation (1)