THERMAL COMFORT AND INDOOR AIR QUALITY IN FORTY-THREE FLIGHTS

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ABSTRACT

This paper reports the results of thermal comfort and indoor air quality studies in forty-three flights with a duration of more than one hour. The measurements were performed continuously during the whole flight (from the departure gate to the arrival gate) and the parameters monitored were temperature, relative humidity and carbon dioxide concentration. The results were then compared with the ASHRAE Standards for the thermal and indoor air quality. The evaluation of the indoor air quality was based mainly upon comparison of the carbon dioxide concentration with standards in indoor environment: carbon dioxide, is an excellent indicator of indoor air quality.

The relative humidity level was far lower than the limit set by the ASHRAE Standard (55-92). The level of carbon dioxide concentration in most of the flight was higher than what recommended by the ASHRAE Standard (62-89).

The low level of humidity and high level of carbon dioxide concentration indicate that the crew and the passengers were dissatisfied with thermal comfort and the quality of the air in the cabin.

KEYWORDS

Thermal Comfort, Indoor Air Quality, Commercial Flights, Passengers

MEASUREMENT TECHNIQUES AND RESULTS

The measurements were carried out during summer of 1996. A total of forty three flights were investigated including four commercial airplane types; Airbus 320, DC9, Boeing 767 and Airbus 340. A portable air sampler was used to measure CO_2, and another was utilized to monitor air temperature and relative humidity. The monitoring was taken between the Hospitality and First Class cabins: the air samplers were programmed to monitor every 5 minutes for the duration of the flight. On all flights, the measurements started right from boarding until the landing.

Thermal Comfort

Air temperature and relative humidity parameters were used as indicator of passengers' thermal comfort. The air temperature was controlled automatically in the passengers cabin nevertheless was set by the crew. The data are grouped into the aircraft types, and Table 1 shows the air temperature and relative humidity for Airbus 320. For each flight, the number of passengers and the altitude are also given. For summer condition (cooling season) ASHRAE Standard 55-92

recommends the mean ambient temperature should be in range of 23 to 26 and the minimum level of relative 20 percents. As indicted in Table 1, the air temperature rarely falls in this range. Data for DC9, Boeing 767 and Airbus 340 are given in Tables 2, 3 and 4.

These tables indicate that the mean air temperature was not regulated fairly well throughout most flights and not within the ASHRAE Standard (ASHRAE 1989); the air temperature falls in the cooler side of comfort zone for summer conditions. As an example, the fourth column in Table 1 shows the range of air temperature in Airbus 320 flights. The lower limit of temperature varies between 19 to 23 (only flight 6/27), and the higher limit of temperature varies between 22 to 26 (only flight 8/4A). The next column in the same table gives the mean air temperature during the flight. It shows that only two flights (6/27 and 7/1) out of fifteen flights satisfies the requirement of summer conditions design. A closer inspection of the data shows that air temperature varies between 21 (which is two degrees lower than the summer condition design) and 24.

It defining the ASHRAE comfort zone for thermal comfort, two assumptions are made: activity level and clothing value. In the case of passengers during a flight, the activity level of 1.2 met is on the high side, however due to lack of sufficient data it is assumed 1.2 met is considered to be acceptable. The Standard also assumes a clothing value of 0.5 clo. for the summer condition design. Using these values (met and clo) and the measured average air temperature and relative humidity, the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) can be calculated. The PMV and PPD indices provide an evaluation of comfort for passengers during the flight. PMV gives values over the range of -3 to +3 corresponding to cold and hot thermal sensation. Since the air velocity was not measured in this study, the indices were calculated for two air velocities; 0.1 m/s and 0.15 m/s. Table 5 shows the PMV and PPD values for A320. As expected from the air temperature and level of relative humidity, PMV values were found to be much below zero, with thermal sensation predicted to be cool (PMV=-1.19) and cold (PMV=-2.49) and PPD ranging from 35 to 86% for air velocity of 0.1 m/s. Table 5 also show the PMV and PPD values for air velocity of 0.15 m/s.

In this calculation, only the clo value of passenger's cloth using the garment values published in ASHRAE Standard 55-92 is used and the clothing value of passenger's seat is not included. The clo value of the passenger can be corrected by adding the clo of the seat. The correction value is proportional to the amount of chair surface area in contact with the body. This modification lifts the average level by 0.5 clo value; increasing the insulation values to 1.0 clo (Doninni et al, 1997). Table 6 shows the PMV and PPD values for the modified clo value. As expected, this extra clo insulation can help the more passengers to accept the thermal environment. The PPD values drop from 86% to 24% for (air temperature of 20.9 and RH 4.). These data also indicate that there is no relationship between the number of passengers and the cabin mean air temperature.

The relative humidity levels were very low in all flights and did not meet even the lower limit of thermal comfort standard. The value average 7% on all the flights tested, and reached values as low as 2%.One interesting result is that the relative humidity level in the DC9 which uses 100% of 'fresh' air, was higher than the relative humidity level in the newer models (Boeing 767, Airbus 320 and Airbus 340) which recycled air. The mean level of relative humidity was even lower than 10% in 17 out of 21 for Airbus 320, 5 out of 15 for DC9, and 4 out of 5 for Boeing 767 flights. From this comparison it seems that the quality of thermal comfort in the passengers cabin in the studies flights was not acceptable.

Ventilation Performance:

Carbon dioxide concentration level was used as the indicator of ventilation performance and indoor air quality. Tables 1 to 4 also give the range of carbon dioxide variation in these flights and the mean concentration level during the flight. These tables show that the levels of carbon concentration in all fights were lower than 5000 PPM. The 5000 PPM which has been proposed by the US Federal Aviation Administration (1993). Part 25 of Airworthness Standard: Transport Category AirPlanes states that "carbon dioxide in excess of 30000 PPM is considered hazardous in the case of crew members". The FAA recently proposed to lower the allowable carbon dioxide concentration in aircraft to 5000 PPM. This level can be achieved with an outdoor air ventilation rate of 2.5 CFM per person. The 5000 PPM level set by the American Conference of Government Industrial Hygienists requires that workers be exposed to an average of no more than 5000 PPM over the period of a week. A closer inspection of data suggests that the carbon concentration levels in some of the flights were exceeded the limit sets by ASHRAE 62-89. As an example, the carbon dioxide concentration level exceeded in 13 out of 22 flights for Airbus, 11 out of 15 for DC9 flights and 1 out of 5 for Boeing 767 flights. It is worth reminding that even though DC9 which had 100 % "fresh air", had higher percentage of flights exceeding the 1000 PPM limit. The ASHRAE Standard sets 1000 PPM of carbon concentration as threshold level for acceptable indoor air quality and carbon dioxide concentration level higher than 1000 indicates lack of ventilation. The 1000 PPM can be achieved with an outdoor air ventilation rate of 10 CFM/person.

The distribution of the air in the cabin is performed uniformly and not on a per passenger basis, therefore, these numbers only indicate the level of carbon dioxide concentration in the first class, where the measurement was taken which has two to three times more fresh air than in the economy class. Therefore, it is expected that the level of carbon dioxide concentration in the economy class be higher than these levels (first class) since the number of passengers per unit area in the economy class is two to three times more. Figures 2-5 also show the general trend of carbon dioxide concentrations with respect to times for several flights. As expected, these high levels occurred during the take off and landing when engine power requirements reduce the amount of compressed air available for ventilation; the level of carbon dioxide concentration drops at cruising altitudes.

Considering that the source of carbon dioxide is passengers, it is expected that fewer passengers on board will result in better air quality. The results however show that these high levels occurred even when some of the flights carried less than 70% of their full passengers capacity. This is probably due to the fact the rate of air circulation is controlled by the pilot and crews and the ventilation rate was kept low for the given flight, since the pilot/crews were mainly concerned with saving energy rather than passengers comfort.

CONCLUSION

In the forty-three flights studied, the level of relative humidity was far lower than the limit set by the ASHRAE Standard (55-92). The level of carbon dioxide concentration in most of the flight was higher than what was recommended by the ASHRAE Standard (62-89). The mean air temperature was not regulated very well throughout most flights. The level of carbon dioxide concentration in some of the flights exceeded the limit set by ASHRAE (62-89).

Judging from the results of this study, mainly the low level of humidity and high level of carbon dioxide concentration, one would expect that the crew and the passengers were dissatisfied with the thermal comfort and quality of the air in the cabin.

REFERENCES

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TABLE 1
Airbus 320 Flight Measurements Summary

Flight No.	ALT (ft)	LOAD (max 137 pax)	TEMP. (C°)	Avg TEMP	Lowest RH (%)	C02 Levels (PPM)	Avg C02 (PPM)
6/27	39000	?	23-24	23.8	5.4	742-1368	5.7
6/28	37000	32	21-23	22.0	3.3	293-664	386.0
6/28A	38000	?	21-23	21.9	3.7	449-1016	538.5
7/1	39000	86	21-24	23.4	1.8	390-938	455.0
7/2	37000	90	21-22	20.9	4.9	351-997	434.6
7/3	39000	65	21-22	21.4	6.2	469-781	565.2
7/3A	37000	62	20-23	22.2	5.2	449-840	532.5
7/5	35000	137	20-22	21.6	13.1	566-1172	753.3
7/5A	39000	49	19-23	22.0	2.6	430-723	478.3
7/6	37000	50	20-23	21.0	2.7	390-958	451.3
7/25	?	60	20-22	21.2	5.8	606-1114	758.0
7/25A	?	4	19-22	20.2	4.4	312-625	408.0
8/2	28000	130	22-24	22.9	18.5	781-1446	1091.2
8/2A	28000	128	20-24	21.7	18.2	781-1231	975.9
8/2B	27000	57	21-25	22.8	15.3	625-1271	821.0
8/2C	37000	137	22-24	22.6	7.6	684-1622	913.6
8/4	35000	103	20-24	22.8	2.5	508-1329	598.2
8/4A	37000	105	20-26	22.8	2.4	508-2013	773.7
8/5	?	?	21-23	22.0	2.3	371-957	446.0
8/8	35000	101	21-23	21.8	4.3	547-1075	527.8
8/9	31000	98	21-24	22.2	2.2	781-1290	1003.8
8/10	37000	63	?	?	?	488-1035	562.0

Table 2
DC 9 Flight Measurements Summary

Flight No.	ALT ft	Load (Max 92 Pax)	TEMP (°C)	Avg. TEMP.	Lowest RH (%)	CO2 Levels (PPM)	Avg.C02 (PPM)
6/28	35000	84	20-24	20.9	11.1	605-1211	785
6/29	26000	26	20-24	21.5	23.0	309-703	497
6/30	32000	60	20-22	20.8	10.9	430-1407	790
6/30A	32000	?	20-24	22.1	8.6	547-1250	847
6/30B	33000	92	21-24	22.8	6.9	567-1446	732
7/6	35000	75	21-24	22.4	7.1	567-996	706
7/6A	33000	60	20-26	22.0	7.3	371-1172	573
7/30	31000	52	22-23	22.7	17.0	625-1055	840
7/30A	33000	60	22-25	22.8	10.8	508-1113	741
7/30B	28000	49	21-22	21.5	9.8	430-645	512
8/1	31000	65	20-21	20.3	19.4	567-1290	751
8/IA	31000	75	21-21	21.0	12.5	723-1309	877
8/IB	33000	66	21-23	22.1	12.0	625-1387	746
8/IC	27000	44	23-24	22.9	15.5		
8/9	35000	65	23-27	23.8	12.3	645-1368	850

Table 3
Boeing 767 Flight Measurements Summary

Flight	ALT	Load	TEMP. (°C)	Avg. TEMP	Lowest RH(%)	C02 Levels (PPM)	Avg.C02 (PPM)
7/10	40000	187/203	22-23	22.9	2.33	488-782	536
7/18	39000	185/203	22-24	22.8	4.51	684-1348	773
7/22	35000	85/195	22-24	23.0	7.63	430-820	602
7/22A	39000	70/195	22-25	23.2	2.3	430-977	565
7/23	35000	35/195	22-27	23.4	1 1.8	469-801	565

Table 4
Airbus 340 Flight Measurement Summary

Flight	ALT	Load	TEMP. (°C)	Avg. TEMP.	Lowest RH(%)	C02 Levels (PPM)	Avg. C02 (PPM)
7/23	39000	177/284	19-24	21	3.3	469-1114	726

TABLE 5: PMV and PPD given by ASHRAE Standard (55-92) (for 0.5 clo and 0.1 m/s air velocity, results in the brackets are given for 0.15 m/s air velocity)

Flight No.	Average Temperature [°C]	Lowest RH [%]	PMV		PPD	
6/27	23.8	5.4	-1.19	(-1.40)	35	(46)
6/28	22.0	3.3	-1.84	(-2.07)	69	(80)
6/28A	21.9	3.7	-1.87	(-2.10)	71	(81)
7/1	23.4	1.8	-1.35	(-1.57)	43	(55)
7/2	20.9	4.9	-2.23	(-2.46)	86	(92)
7/3	21.4	6.2	-2.04	(-2.27)	79	(87)
7/3A	22.2	5.2	-1.75	(-1.98)	64	(76)
7/5	21.6	13.1	-1.92	(-2.15)	73	(83)
7/5A	22.0	2.6	-1.84	(-2.07)	69	(80)
7/6	21.0	2.7	-2.21	(-2.43)	85	(92)
7/25	21.2	5.8	-2.11	(-2.34)	82	(89)
7/25A	20.2	4.4	-2.49	(-2.71)	93	(97)
8/2	22.9	18.5	-1.40	(-1.63)	45	(58)
8/2A	21.7	18.2	-1.85	(-2.08)	69	(80)
8/2B	22.8	15.3	-1.46	(-1.69)	49	(61)
8/2C	22.6	7.6	-1.59	(-1.82)	56	(68)
8/4	22.8	2.5	-1.55	(-1.79)	54	(66)
8/4A	22.8	2.4	-1.55	(-1.79)	54	(66)
8/5	22.0	2.3	-1.85	(-2.08)	69	(80)
8/8	21.8	4.3	-1.91	(-2.14)	72	(83)
8/9	22.2	2.2	-1.77	(-2.01)	66	(77)

TABLE 6: PMV and PPD given by ASHRAE Standard (55-92) (for 1.0 clo and 0.1 m/s air velocity, results in the brackets are given for 0.15 m/s air velocity)

Flight No.	Average Temperature [°C]	Lowest RH [%]	PMV		PPD	
					6	(7)
6/27	23.8	5.4	-0.21	(-0.31)	15	(18)
6/28	22.0	3.3	-0.68	(-0.80)	15	(19)
6/28A	21.9	3.7	-0.69	(-0.82)	7	(9)
7/1	23.4	1.8	-0.33	(-0.44)	24	(29)
7/2	20.9	4.9	-0.94	(-1.07)	19	(23)
7/3	21.4	6.2	-0.81	(-0.94)	13	(16)
7/3A	22.2	5.2	-0.61	(-0.73)	16	(20)
7/5	21.6	13.1	-0.71	(-0.84)	15	(18)
7/5A	22.0	2.6	-0.68	(-0.80)	31	(38)
7/6	21.0	2.7	-1.11	(-1.26)	20	(26)
7/25	21.2	5.8	-0.86	(-0.99)	31	(38)
7/25A	20.2	4.4	-1.12	(-1.26)	7	(9)
8/2	22.9	18.5	-0.33	(-0.45)	14	(18)
8/2A	21.7	18.2	-0.65	(-0.78)	8	(10)
8/2B	22.8	15.3	-0.39	(-0.50)	10	(13)
8/2C	22.6	7.6	-0.49	(-0.61)	10	(13)
8/4	22.8	2.5	-0.48	(-0.60)	10	(13)
8/4A	22.8	2.4	-0.48	(-0.60)	15	(19)
8/5	22.0	2.3	-0.68	(-0.81)	16	(20)
8/8	21.8	4.3	-0.72	(-0.85)	13	(17)
8/9	22.2	2.2	-0.63	(-0.75)		