CH-81-17 No. 3

EVALUATION METHODS FOR AIR VELOCITY MEASUREMENTS IN AIR-CONDITIONED ROOMS

DR-ING. BRUNO GRÄFF

ABSTRACT

The uncertainty of measurement results of air velocities in air-conditioned rooms generally is very high. A considerable part of the measurement errors are caused by the evaluation methods.

It is shown that the accuracy of results can be ameliorated by using suitable statistical methods without increasing the effort. In this case binomial distribution gives better results than Gaussian distribution.

To optimize the duration of measurements the most favorable reading interval must be determined. This time interval can be defined by the autocorrelation function of air velocity.

1. INTRODUCTION

Air-conditioning's main task is to provide and to maintain the necessary environmental conditions for technical and biological processes. In these processes, mass transfer and energy transfer take place to change the conditions in the room without any external influences.

To maintain the required conditions, air-conditioning systems generally utilize air currents capable of equalizing the energy load and the mass load in the room. The air supply to the conditioned room and also the air exhaust greatly influence the velocity, temperature and mass concentration distribution.

The analytical models used today to predict the velocity, temperature and concentration distributions in concluded air spaces differ in approach and feature major uncertainties.

For high air velocities (for instance, in industrial air conditioning) a large number of empiric equations allow a fairly accurate and useable prediction for various geometries of air inlets and various room configurations.

In rooms occupied by people and in a space that includes many obstacles, predictions based on these empirical equations are very difficult, if not impossible. These are the reasons why experimental approaches are generally used to obtain the data for the air-conditioning systems. Models (very often in scale 1 to 1) used in these approaches normally feature highly variable air velocities.

Dr.-Ing. Bruno Gräff is University Lecturer, University of Essen, D 4300 Essen, Germany

To evaluate the thermal comfort it is necessary to consider the time variation of this air motion. Today, measurements and evaluation methods of air velocities in air-conditioned rooms are insufficient to prove exactly if complaints about drafts have real causes.

THE GOAL OF MEASURING AIR VELOCITIES IN AIR CONDITIONED ROOMS

The turbulent jet ventilation used today produces very large variations of air velocity in air-conditioned rooms. Fig. 1 shows typical air velocity variations.

The data in Fig. 1 show a lot of information which is very difficult to handle. To fix, for instance, the guaranteed data it is necessary to reduce the entire information to a few values. With this method we always have a remarkable loss of information.

Because mass flow caused by diffusion can not reduce the concentration of air contamination to the right value, it is necessary to change the air completely in all parts of the room, and therefore we need a prediction of air velocity in the ambient zone. For this prediction it is only necessary to know the mean value of air velocity.

Further air motion must be valuated with regard to drafts. There is no doubt that air velocity has a major influence on thermal comfort, and therefore the air motion must be well designed to be able to avoid any draft.

At particulary mean value of air velocity it is possible to feel a draft if there is a strong variation of velocity in a short time; but without any significant variation the same mean value will not cause any noticeable draft.

A lot of investigations have been made to correlate the variations in air velocity with thermal comfort. The main goal of measuring air velocities is the determination of repeatable values which predict the mean value and the standard deviation.

Because the variations show a random trend it is necessary to analyze the measurements optimaly using determinated statistical means. In particular, it is not permissable to utilize statistical distribution laws which have not been carefully demonstrated to be applicable.

CURRENT ANALYSIS METHODS

The analysis methods used today to derive characteristic values for the determination of the main trend of air velocities and the variation of the values at specific times are based on the hypothesis of the Gaussian distribution. Methods without any specific distribution laws are very seldom used.

Until now it was impossible to prove that velocities at any instant in air-conditioned spaces fit the normal distribution. Quite to the contrary, existing facts indicate that the velocity does not follow the law of normal distribution. The use of the wrong hypothesis for velocity variations causes major errors in the results.

The analysis of velocity measurements by a method not using anly law of distribution gives the correct characteristic data for the specific sample being considered. However, these measurement results do not provide enough information regarding the overall trend of velocity.

The velocity measurement may include significant errors caused by the sensor because its output depends on the flow direction which is not considered in this paper. In addition errors may be caused by using the wrong sampling technique; i. e. the result may be wrong if the sampling method is not representative for the velocity distribution.

3.1 Analysis Using Gaussian Distribution

To be able to use the normal distribution for analyzing measurements of velocities, it is necessary to have a large number of instant values of velocity at the same location. These values must be classified either on the basis of a time method or by a sampling method.

In using the first method, the sum of all times t_i must be counted and the instant velocity can be determinated in each classification range (Fig. 2). The relative frequency can be derived as the sum of the times in each velocity range divided by the total time T of the measurement.

For analysis purposes relative cumulative frequency is generally used. We determine this value by summarizing the times t_i during which the instant velocity is lower than the lower limit of the specific velocity range and dividing by the total time of the measurement.

The sampling method uses the instant velocities in each range at preselected time intervals. The measurements can be made in fixed time intervals or in random intervals. The latter can prevent errors due to the influence of a periodical behavior of the velocity distribution. Generally the measurements are made with constant time intervals t_t. This way of analyzing is shown in Fig. 3 as an example. To perform sampling it is necessary to have definite time intervals Δt. Δt must be small to permit exact measurements.

The number of instant velocity sample values in the particular velocity range must be divided by the total number of values. This result is equal to the relative class frequency.

Statistical characteristic values, generally the 50%-value and the 84%-value, are derived from either the class frequency or the cumulative frequency. Postulating the Gaussian distribution we obtain the characteristic values very quickly using the probability paper (Fig. 4).

The 50%-value is normally regarded equal to the mean value $\bar{w}$ and the 84%-value equal to the sum of the mean value and the standard deviation $\bar{w} + s_w$.

3.2 Analysis Without Postulated Distribution Law

The mean value and the standard deviation can also be derived without using the Gaussian distribution. In this case the sampling data are used directly and we get the mean value by the following equation:

$$\bar{w} = \frac{1}{n} \sum_{i=1}^{n} w_i \qquad (1)$$

and the standard deviation:

$$s_w = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (w_i - \bar{w})^2} \qquad (2).$$

Errors caused by postulating the wrong distribution can be prevented by this method, which delivers only calculated characteristic values but not the instant velocity distribution.

4. NEW ANALYSIS METHOD

In the new draft of German standard DIN 1946 the 50%-value and the 84%-value are used to describe the influence of air flow on draft in air-conditioned rooms. The 50%-value must be lower than a specified velocity limit and the 84%-value must be lower than a somewhat higher velocity limit.

The difference in approach seems to be very small but it has very important consequences with respect to: 1. principles, and 2. measurement techniques.

1. Principles
If it is necessary to derive the 50%-value and the 84%-value of velocity, we must use an unproved,and in most cases, wrong distribution law and then compare these results with velocity limits according to regulations.

If only the percentage of allowable sample values must be determined, we have with this percentage an unbiased estimate of the parameter p of a well-known distribution - the binomial distribution.

2. Measurement Techniques
To find out the 50%-value and the 84%-value of velocity based on the hypothesis of Gaussian distribution, it is necessary to obtain sufficient measurement accuracy to determine the empiric frequency distribution with a large number of classes.

To analyze the velocity with the binomial distribution, only one velocity range needs to be recorded. By using this approach a better theoretical basis for analyzing is achieved than with the Gaussian distribution.

4.1 Binomial Distribution

If we classify the instant velocities, whether they are in the allowable range or outside, we obtain the following relationship for the relative frequency of velocities in the allowable range:

$$h_z = \frac{\nu}{n} \qquad (3)$$

with ν allowable values from n sample values.

The relative frequency of the unallowable values is

$$h_u = \frac{n-\nu}{n} \qquad (4)$$

If n becames infinite the relative frequency will be equal to the probability.

Proposing p as the probability of the allowable values and 1-p as the probability of the unallowable values we can determine, based on the binomial distribution, the probability of ν values in the allowable range in a sample of total number of values n:

$$f(\nu) = \binom{n}{\nu} p^{\nu} (1-p)^{n-\nu} \qquad (5)$$

For practical purposes it is not possible to predict the probability of the allowable values in a sample because the parameter p of the binomial distribution is normally unknown. This parameter must be determined based on the number of acceptable values ν in a particular sample size. To find the inaccuracy using a small sample size, the following approach is useful:

Using p_o as a comparison parameter and α as the degree of risk for errors of first order we can establish the hypothesis $p = p_o$. (For instance, this means $p_o = 0.5$ if at least 50% of the values are in the allowable range.) To avoid accepting samples with a too small parameter p, we test the alternative hypothesis $p < p_o$. With a fixed sample size n we can calculate the upper limit k_o based on the binomial distribution with a degree of risk lower than or equal to α. If there are more than k_o acceptable values in the considered sample, we have to decide in favor of the hypothesis $p \geq p_o$ instead of the hypothesis $p < p_o$.

The risk of errors of the first order, meaning that the hypothesis $p \geq p_o$ is not used though it is correct, is smaller than or equal to α. The risk of errors of the second order, which exists by accepting the hypothesis though it is wrong, remains unknown. With $1-\beta(p)$ as the probability of risk of these errors, we obtain the equation

$$1-\beta(p) = \sum_{\nu=0}^{k_o-1} \binom{n}{\nu} p^{\nu} (1-p)^{n-\nu} \qquad (6)$$

Eq 6 defines the operating characteristic, and it allows the calculation of errors of the second order if the risk of error of the first order and the size of the sample are known.

The calculation of this operating characteristic is difficult and therefore it is better to describe the operating characteristic in the range of main interest as a diagram which is shown in Fig. 4. This diagram can be used to minimize the number of measurements. For instance, if it is necessary that fewer than 50% of the instant velocity values in an acceptance test lie in the allowable range with an error less than 5%, then it is necessary that the risk of errors of the first and second orders are both less or equal to 5%.

If the probability for acceptable values is declared as $p = 0.75$ the number of sample values must be at least $n = 50$. If we get 32 or more sample values in the allowable range we can establish that at least 50% of all instant velocity values in the population are acceptable. The diagram shows that the risk of errors $1-\beta(p)$ is about 3.5%.

4.2 Selection Of Time Intervals

To obtain representative data it is necessary for all analysis methods to have independent velocity values. To obtain independent values we need sufficiently long time intervals between taking the data. To determine the optimum interval t_t we can use the autocorrelation function

$$A_{ww}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} w(t) \cdot w(t+\tau)\, dt \qquad (7)$$

where:

- t = time
- τ = time interval between 2 readings
- T = total measuring time
- w = velocity

Fig. 5 shows the autocorrelation function of velocity at one point in the ambient zone of an air-conditioned room. At small intervals, τ, the function $A_{ww}(\tau)$ is near $\overline{w^2}$, i. e. the values are not independent but they decrease quickly. When A_{ww} drops to $\overline{w}^2$ the velocity values are independent.

The time t_t can be chosen by drawing a rectangular area equal to the area between the ordinate, the autocorrelation function and the $\overline{w}^2$ line, as shown in Fig. 5. With the determined time interval, each value shows only little correlation to the values before and after, and there is no significant correlation to the rest of the sample's n-3 values. With a large sample it is therefore possible to consider special values of the sample to be independent from each other.

5. CONCLUSION

Results of velocity measurements in air-conditioned spaces have generally a high inaccuracy, which is caused by the sensor of the anemometer and by the evaluation method used.

The errors in the evaluation method are caused mostly by using a wrong hypothesis of the velocity distribution and by too short intervals between readings of measured values.

The proposed approach determines the risk of error in a simple way. Also it allows for use of a correct hypothesis of distribution and for optimizing the sample's size. It is possible to avoid the correlation between particular sample values by determination of a minimum reading time. With the minimum reading time and the correct sample size, the total measure time for air velocities in air-conditioned rooms can be optimized.

BIBLIOGRAPHY

1. Fanger P.O.: Thermal Comfort. Danish Technical Press. Kopenhagen (1970)

2. Gräff B.: Possibilités et limites de prédire le courrant d'air dans des chambres climatisées. Institut International du Froid, Commission IV, Wien (1973), pages 293-302

3. Gräff B.: Statistik in der Klimatechnik. Verlag C.F. Müller (1974)

4. Gräff B., Pfeiffenberger U.: Betrachtungen zur Optimierung der Meßdauer bei Raumströmungsuntersuchungen. DKV-Tagungsbericht, Nürnberg (1974)

5. Gräff B.: Bewertungsverfahren für Messungen von Luftgeschwindigkeiten in klimatisierten Räumen. Forschungsberichte des Deutschen Kälte- und Klimatechnischen Vereins, Nr. 2 (1980)

6. Nouri Z.: Anwendung statistischer Verfahren bei experimentellen Untersuchungen von Raumluftströmungen. Heizung-Lüftung-Haustechnik 29 (1978) 4, 5, 6

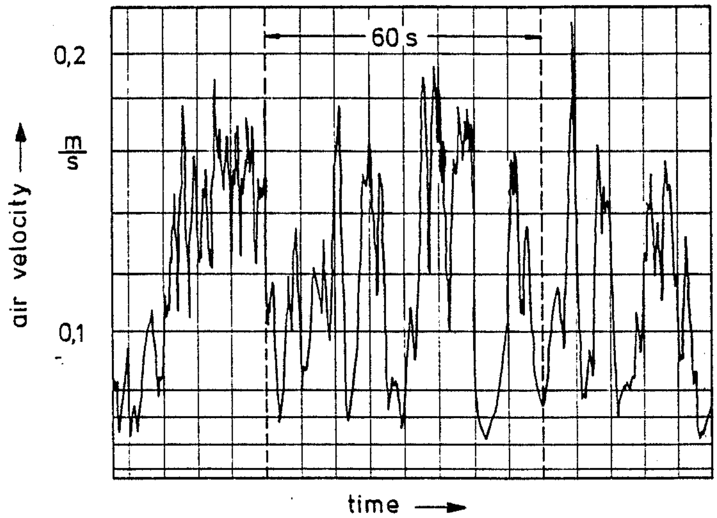

Fig. 1 Air velocity in an air-conditioned room

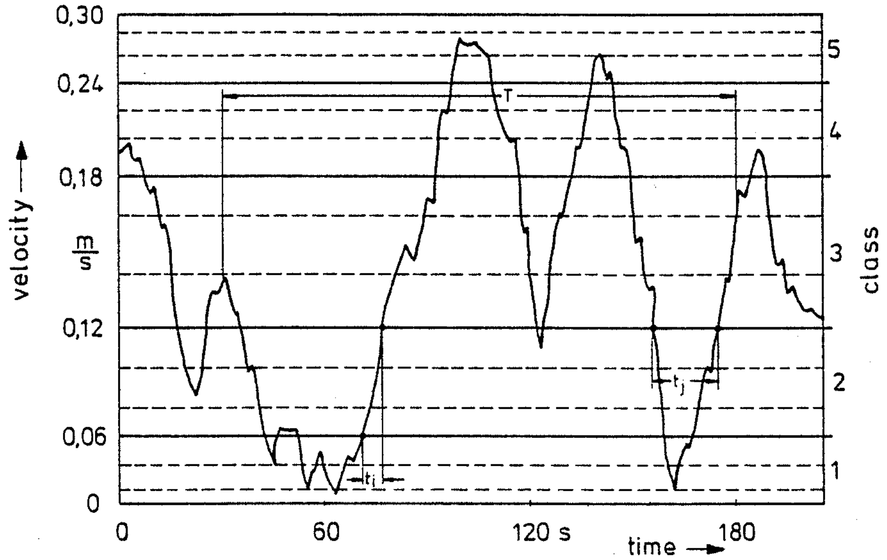

Fig. 2 Time method

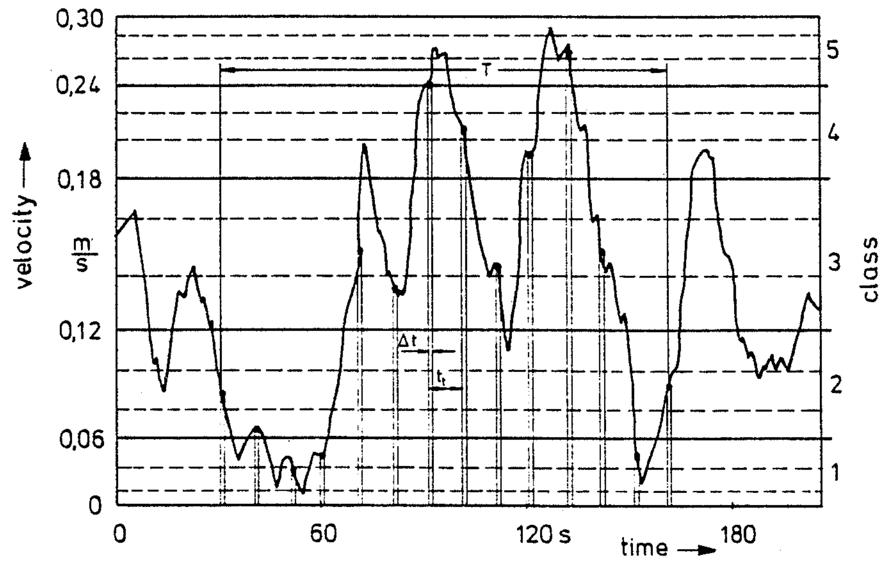

Fig. 3 Sampling method

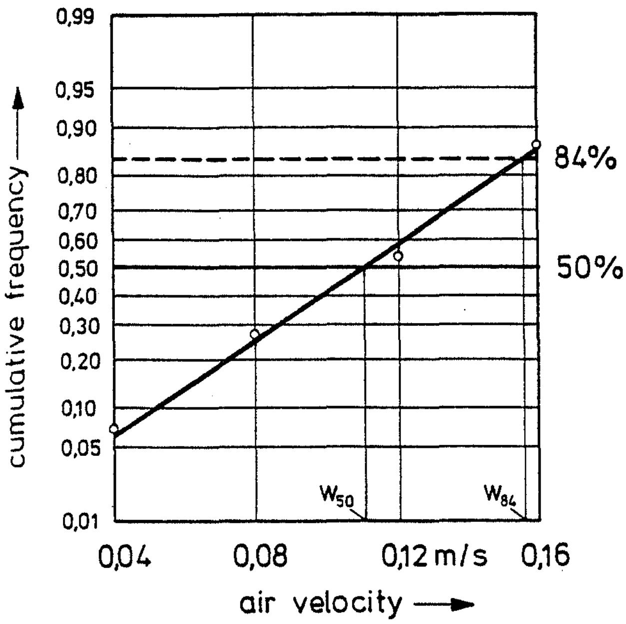

Fig. 4 Determination of the 50%-value and the 84%-value

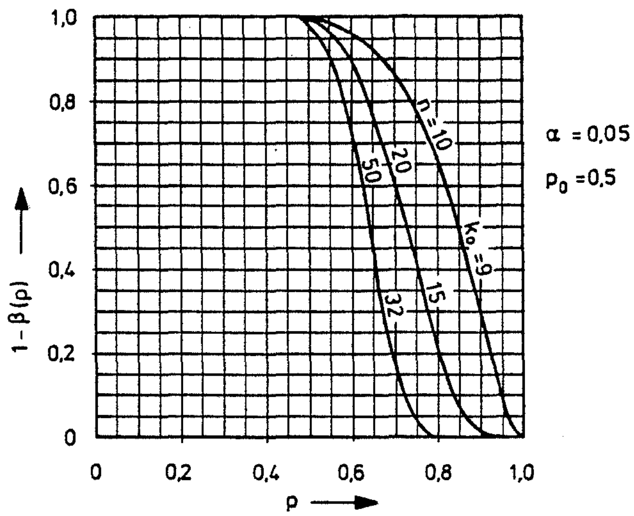

Fig. 5 Operating characteristic of a binomial distributed population

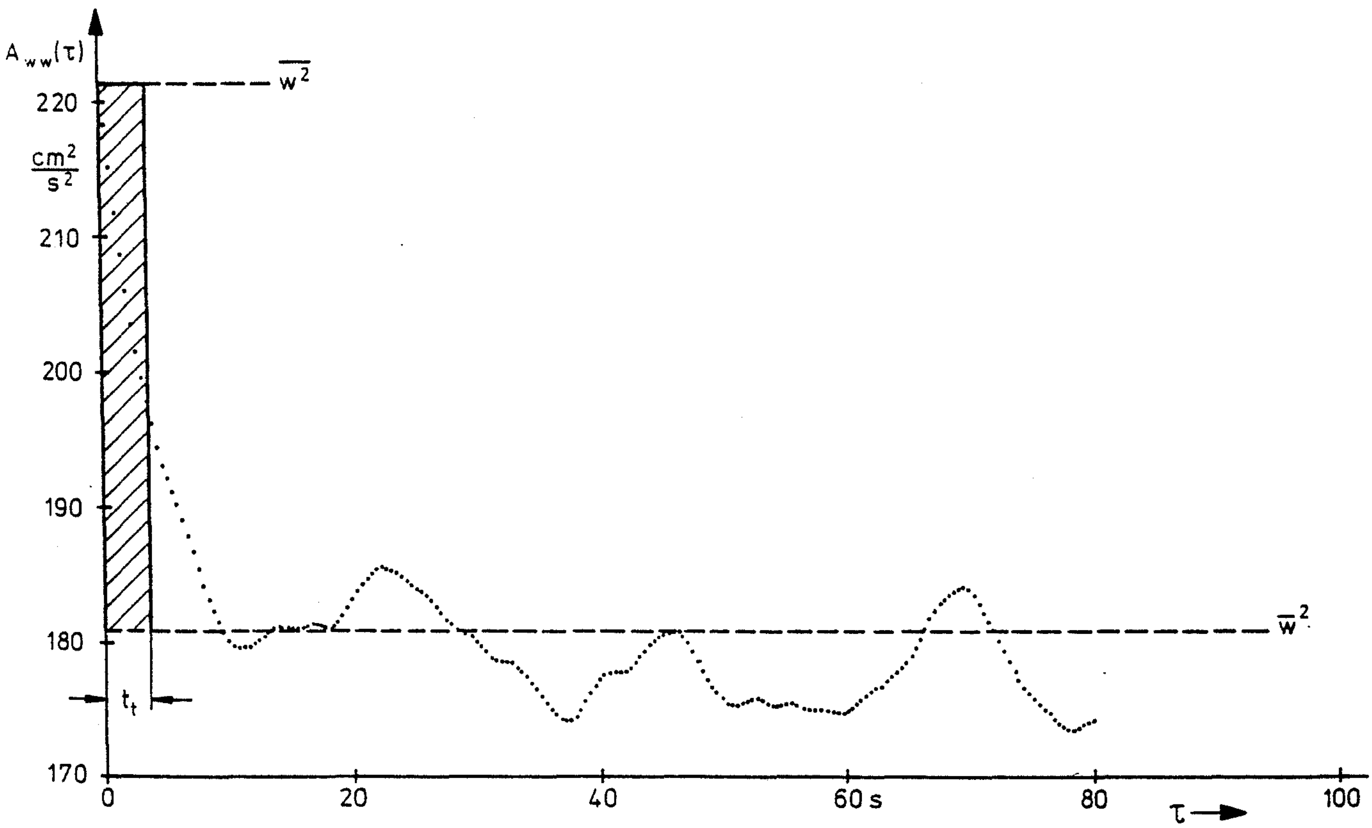

Fig. 6 Optimization of reading time