ROOM -VENT '90

Comparatory tests of omnidirectional and hot wire anemometers

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COMPARATORY TESTS OF OMNIDIRECTIONAL AND HOT WIRE ANEMOMETERS

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Measurements of parameters of turbulent air streams and secondary flows play an essential role in tests of room ventilation processes. Turbulent flows are characterized by means of mean velocity vector and quantities describing velocity fluctuations.
Those parameters have been measured so far usually with the use of anemometers that isolate velocity components.
Recently, many tests of thermal comfort conditions in rooms (1,2) have been carried out with the use of omnidirectional anemometers, measuring modules and not velocity components and their fluctuations.
The production of these equipment is still growing, they facilitate measurements and therefore are handy in air motion tests in rooms.
However, owing to different measurement characteristics, measurement results obtained with the use of an omnidirectional anemometer should not be interpreted in the same way as hot wire anemometer readings.

1. Features of the tested anemometers.

The tested anemometers differ in directional and dynamical properties as well as in spatial resolution.
Anemometer signal corresponds to a certain instantaneous value of the flow velocity that is "felt" by the sensor as the effect of cooling of the heated element. That velocity is called the effective velocity w_{ef}. Its value corresponds to the actual instantaneous velocity w, when the direction of w and of the assumed main measurement axis of the anemometer sensor are the same.

A hot wire anemometer, for velocities higher than 20 m/s, reacts to two components of the velocity vector :

$$W_{ef}^2 = W_x^2 + W_y^2$$

(1)

For lower velocities, the probe design is also considered i.e. the finite length of the wire and the presence of holders. According to Jørgensen, the relation between w_{ef} shown by a hot wire anemometer signal and the stream flow direction determined by the components of the air instantaneous velocity vector is as follows:

$$W_{ef}^2 = W_x^2 + k_1^2 W_y^2 + k_2^2 W_z^2$$

(2)

where k_1 and k_2 are factors including the effect of the velocity vector

direction towards the hot wire axis.
According to Reynolds' hypothesis, it can be assumed that:

$$W_{ef} = \overline{W}_{ef} + W'_{ef}$$

(3)

where $\overline{W}_{ef}$ and w'_{ef} are mean and fluctuaction value of the effective velocity when mean velocity direction is perpendicular to the hot wire axis. Thus:

$$W_x = \overline{W} + W'_x \quad , \quad \overline{W}_y = \overline{W}_z = 0$$

$$W_y = W'_y \quad , \quad W_z = W'_z$$

(4)

The effective velocity may be described by the relation in which that direction is distinguished:

$$W_{ef}^2 = (\overline{W}_x + w'_x)^2 + k_1^2 w_y'^2 + k_2^2 w_z'^2$$

(2a)

Expansion of the above equation in a power series including the terms with fluctuation correlation not greater than those of 4 th order yields a formula, owing to which it is possible to evaluate the effect of turbulence intensity on the effective velocity value (3) :

$$W_{ef} = \overline{W} + W'_x + \frac{k_1^2 w_y'^2 + k_2^2 w_z'^2}{2\overline{W}} - \frac{k_1^2 w'_x w_y'^2 + k_2^2 w'_x w_z'^2}{2\overline{W}^2} -$$

$$+ \frac{k_1^4 w_y'^4 + k_2^4 w_z'^4}{8\overline{W}^3} + \frac{k_1^2 w_x'^2 w_y'^2 + k_2^2 w_x'^2 w_z'^2}{2\overline{W}^3} - \frac{k_1^2 k_2^2 w_y'^2 w_z'^2}{4\overline{W}^3}$$

(5)

The above equation shows that discrepancies between instantaneous values of the effective velocity and of the longitudinal component increase when the flow turbulence gets higher.
A hot wire anemometer has a small lag which makes it possible to read fluctuations of frequencies above 1000 Hz. Since the sensor size is small, the anemometer has high spatial resolution.

A hot sphere sensor of an omnidirectional anemometer does not separate any direction in the space as the measurement axis. Therefore, a hot sphere anemometer reacts to the instantaneous velocity vector. Thus:

$$W_{ef} = |W| = (W_x^2 + W_y^2 + W_z^2)^{0.5}$$

(6)

In this case the parameters characterize the air motion and they cannot be used to determine the instantaneous velocity vector.
A hot sphere anemometer inertia is significantly higher than in the case of a hot wire anemometr and this fact affects also the character of the output signal. Owing to the larger size, its spatial resolution is worse as

well. The above features of both anemometer types, resulting from shape and design of the sensor, prove that the readings of turbulent flow parameters are different for the both devices. This affects the way of signal interpreting and comparing and the scope of applicability of those anemometers.

2. The effect of flow type on anemometer readings.

Air flows observed in ventilation processes can be divided into two groups, namely:

Low turbulence flows , Tu<25%, in which the instantaneous value of the effective velocity is approximately equal to the instantaneous value of the velocity vector longitudinal component. In this case, the terms including fluctuation products of the second and higher order can be neglected in Eq.5(3). Therefore, the variance of the effective velocity fluctuations is equal to the variance of longitudinal fluctuations of the velocity vector. These relations can be a sufficient aproximation of air flows in ducts and free streams in ventilation processes. In those cases the same or similar readings of hot wire and hot sphere anemometer can be expected.

It is worth mentioning, however, that locally the readings may substantially differ e.g. in places or cross-sections of the stream where whirls occur. The turbulence structure is received there in different ways owing to different dynamical properties of the sensors.

Flows of high turbulence intensity, Tu>25 %, when factors including fluctuation products cannot be neglected in Eq.5. In these cases turbulence intensity and structure in a given location of the stream, substantially affect both the mean value and the effective velocity variance. Thus, in highly turbulent flows, interpretation of hot wire anemometer readings gets very complicated which may result in too big errors when determining flow parameters and the device may be useless.

Highly turbulent flows occur in ventilated rooms in secondary flow zones or in flows defined as draught. In those cases we would be interested in measurement of sensed i.e. effective velocity of air movement, with no information of the movement direction. It is interesting to determine the mean effective velocity and the effective velocity fluctuations in that movement. Those are the information given by a hot sphere anemometer. A hot wire anemometer practically does not suit the purpose.

From the above discussion it appears that :

- When testing flows of low turbulence intensities, both types of anemometers may be used while the measurement results are interpreted according to their directional and dynamical properties.
- When testing flows of high turbulence intensities, omnidirectional anemometer readings may still be accurate if their interpretation is restricted only to module values. Hot wire anemometer readings get worse and even lose their sense as turbulence intensity increases.
- When interpreting results of comparatory measurements of any parameters, dynamical properties of the compared anemometers should be taken into account.

3. The way of measurements of parameters characterizing flow.

Some comparatory tests of anemomometers were carried out in order to verify experimentally the conclusions drawn in Chapter 2 and, in particular, to check measurement results discrepancies, when :

- for flows of low turbulence intensity, measurement convention

characteristic of hot wire anemometers was applied for both types of anemometers
- for flows of high turbulence intensity, measurement convection characteristic of hot sphere anemometer was applied for both types anemometers
- for flows of low and high turbulence intensity, measurements and calculation conventions proper for each anemometer type were applied

The following anemometers were selected for the comparatory measurement :
- a hot sphere anemometer, type HST-1, designed and produced at the Silesian Technical University (Fig.1a)
- a hot wire anemometer, type DISA 55P81 with automatic temperature compensation, used so far mainly for measurements of ventilating air distribution (Fig.1b).

a.

b.

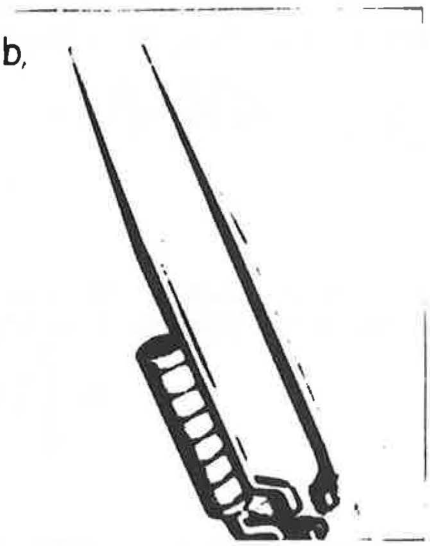


Fig.1. The sensors of the compared anemometers
a. hot sphere HST-1
b. hot wire DISA 55P81

The measurements were carried out in a test chamber. The measurement stand included a measurement system employing digital registration and result processing technique. The computer program made it possible to register signals of both anemometers simultaneously by means of the off-line method.

Low turbulence flow occured in the supply air stream, where the mean velocity direction was approximately the same as that of the longitudinal x axis. The parameters were measured in two cross-sections of the stream:
$x/d_N = 6.7$ when $w_N = 1.5$ m/s
$x/d_N = 13.3$ when $w_N = 1.5$ m/s and $w_N = 3.5$ m/s
High turbulence occurred in the secondary flow zone, where the mean flow direction was not determined. Measurements were made in one cross-section: $x/d_N = 33.3$ when $w_N = 3.5$ m/s.

In order to compare the measuring properties of both the anemometers, instantaneous effective velocities of air were measured at conveniently chosen averaging time and on this basis the following values characterizing the flow, were determined:

A. Distribution function of instantaneous velocity values, determined after the definition for both anemometers at the assumed averaging time.

B. The flow mean velocity:
for the hot sphere anemometer determined as the mean effective velocity,
for the hot wire anemometer as the mean effective velocity when the flow direction was the same as the direction of the measurement main axis of the sensor
C. Standard deviation of velocity fluctuations:
for the hot sphere anemometer determined as the effective deviation,
for the hot wire anemometer determined as the effective deviation at perpendicular position of the wire to the axes x or z.

For the direction y, the deviation was evaluated assuming low turbulence of the flow, according to the method presented in (3,4).

$$\overline{w_y'^2} = \frac{[\overline{w_{ef}'^2(\alpha=45°) + w_{ef}'^2(\alpha=-45°) - w_{ef}'^2(\alpha=0°)(1+k_1^2)}](1+k_1^2)}{(1-k_1^2)^2}$$

(7)

D. Macro-scale of length, for both types of anemometers determined on the basis of Taylor's hypothesis on whirl structure freezing (5):

$$L = \overline{w}_x \int_0^\infty \rho(\tau_p)\, d\tau_p$$

(8)

The autocorrelation coefficient depending on the lag time was determined by means of the method described in (4).

E. Micro-scale of length, for both types of anemometers determined by micro-scale of time (5),which was calculated directly from the definition (3,5):

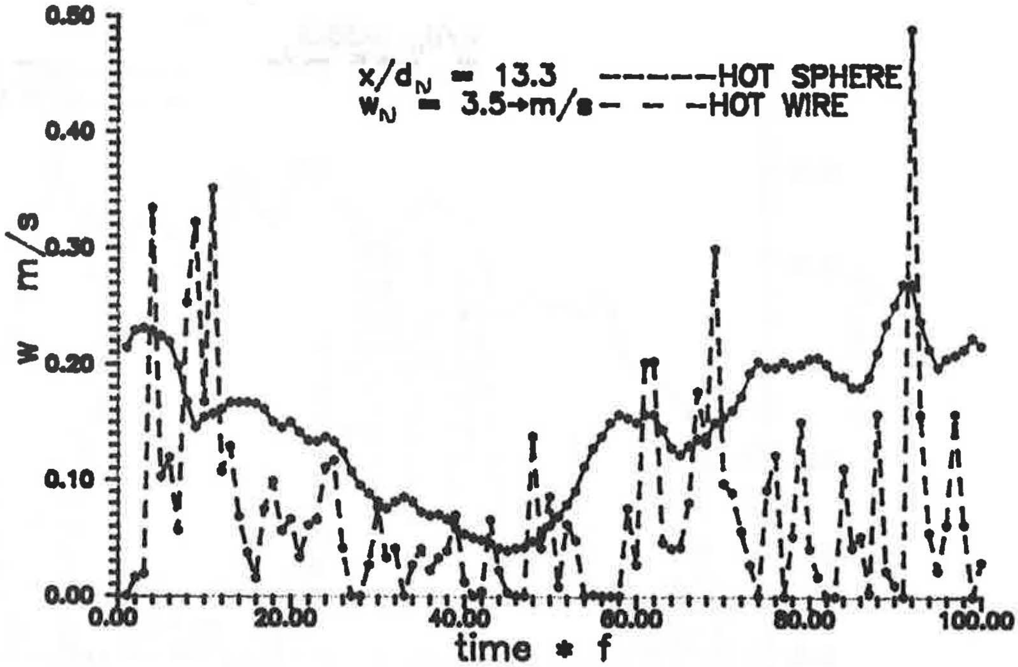
$$\tau_m = \left[\frac{\overline{w'^2}}{\left(\frac{\overline{\partial w_x}}{\partial x}\right)^2}\right]^{0.5}$$

(9)

The instantaneous value of the velocity derivative was determined employing the formula of numerical derivation.

6. Comparison of the values of parameters measured directly.

Fig. 2a,b show directly measured instantaneous effective velocities in some points of the stream and the secondary flow zone for fragments of the averaging time and the distribution of this velocity for the whole averaging time.



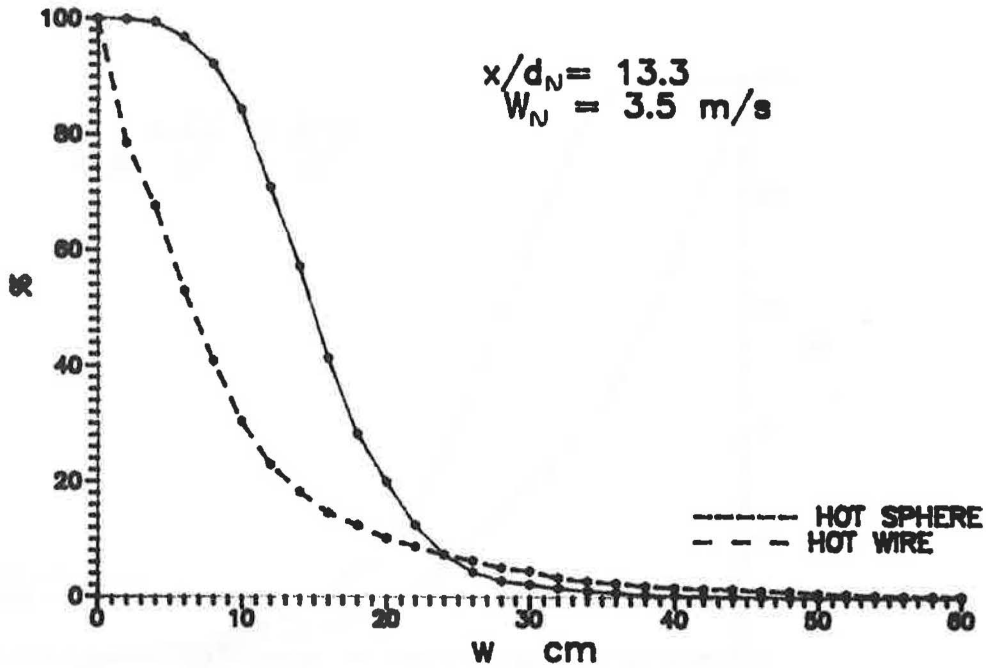
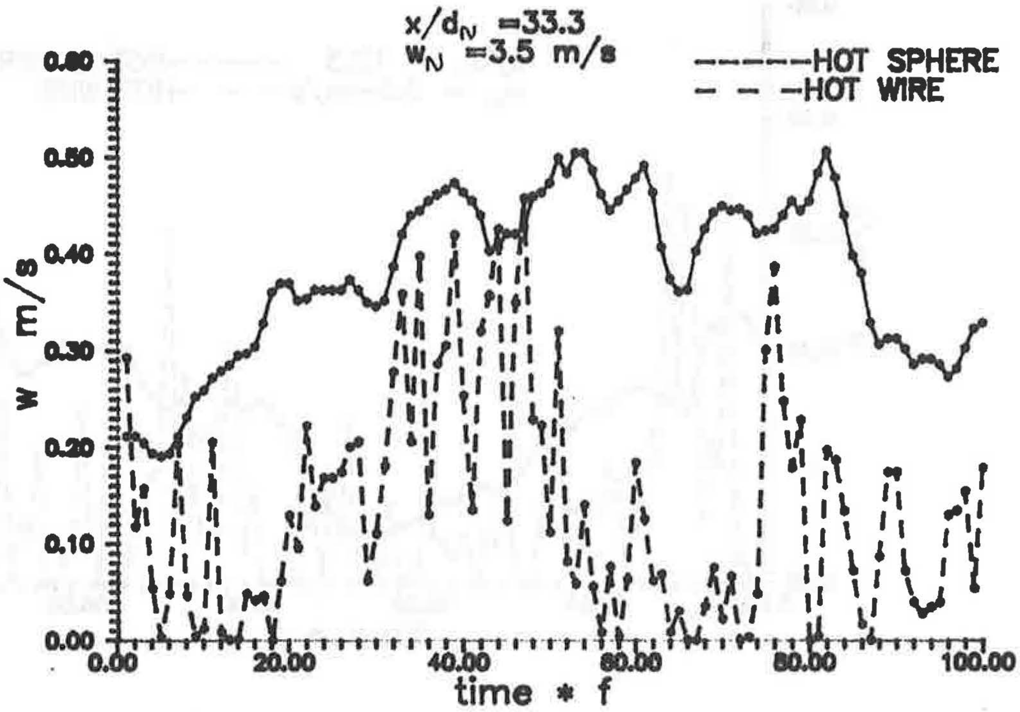


Fig.2a. Instanteneous values of effective velocities and their distribution function in the selected point according to the readings of both anemometers when w_N =3.5 m/s in the supply air stream, h = -5 cm



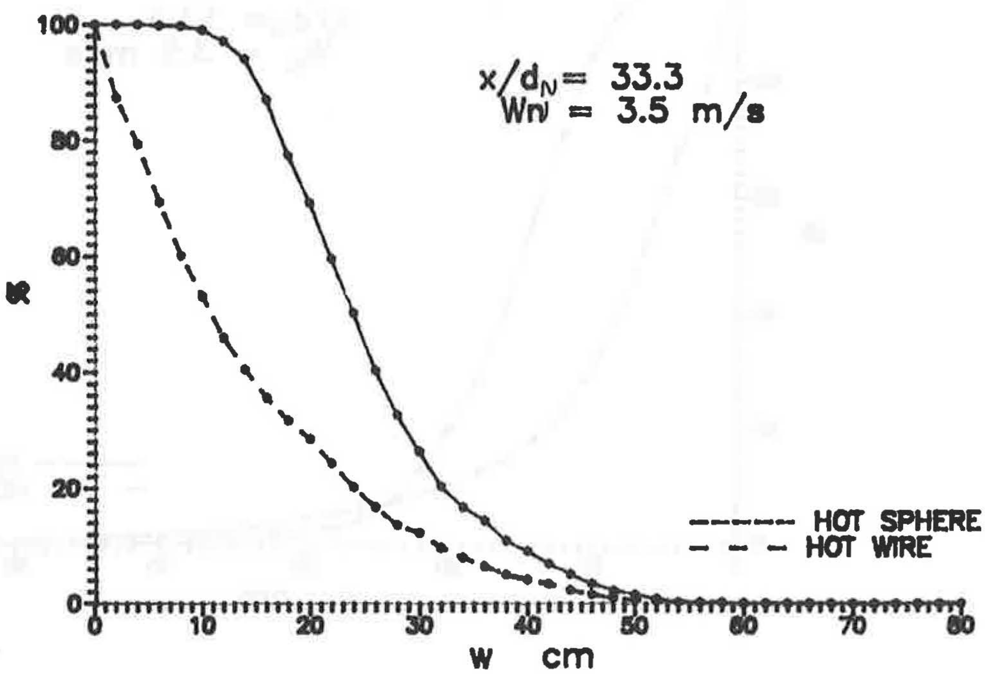


Fig.2b. Instanteneous values of effective velocities and their distribution function in the selected point accordings to the readings of both anemometers when w_N = 3.5 m/s in the secondary flow zone, h = 7 cm

When comparing the measurement results it is apparent that the hot sphere anemometer readings are not the same as the readings of the hot wire anemometer and the value displayed are higher.Moreover, the hot sphere anemometer causes averaging and dumps fluctuations of higher frequencies which is related to significant inertia of the device.

As far as the mean effective velocity, characterizing the mean flow, is concerned, it was found that:

- in the supply air stream the values shown by the hot sphere anemometer were higher from 5 to maximum 20% than those shown by the hot wire anemometer (Fig.3a).
- in the secondary stream zone the values shown by the hot wire anemometer were even 30 up to 50% smaller than those shown by the hot sphere anemometer (Fig.3b).

Comparison of parameters describing flow turbulence structure proved that with respect to standard deviations of velocity fluctuations in the tested cases:

- the values read from the hot sphere anemometer for the supply stream were smaller than those read from the hot wire anemometer in maximum 55% (Fig. 4a)
- for the secondary flow zone the values read from the hot wire anemometer were also higher in about 30 % (Fig. 4b).

Those discrepancies resulted not only from the directional properties of the anemometers but also from their dynamical characteristics. Owing to the high time constant of the hot sphere anemometer, not all the fluctuations could be measured by it and each one shown was a value of some samples averaged in time.
Turbulence scales were compared too, in consideration of the fact that those parameters cannot be measured precisely by means of a hot wire anemometer when it is perpendicular to the longitudinal direction, though so far the device has been most often used to that type of measurements
With respect to the length macro-scale it was found that both for the supply stream and for the secondary flow zone the values measured by the hot sphere anemometer were overstated in relation to the hot wire anemometeter and the discrepancies reached up to 800 % (Fig.5).
With respect to macro-scale it was found that the results obtained by means of the hot sphere anemometer reached the values that were physically unreal.They were higher than the values measured by the hot wire anemometer up to 10 times and the discrepancies increased in the zone of higher turbulence intensity of the flow, (Fig.6).
The results of the measurements of turbulence scales with the hot sphere anemometer have proved that the device is useless for measurements of this type.
It is above all related to its dynamical characteristics since only correlations between groups of fluctuations and not between instantaneous fluctuations are indicated by means of this anemometer.

7. Comparison of results of complex parameters measurements.

Having compared the results of direct measurements of flow parameters, one can also compare some complex values, determined on the basis of the parameters measured directly while applying measurement and calculation conventions proper for each type of anemometer.

One of these complex parameters may be the mean square value of the

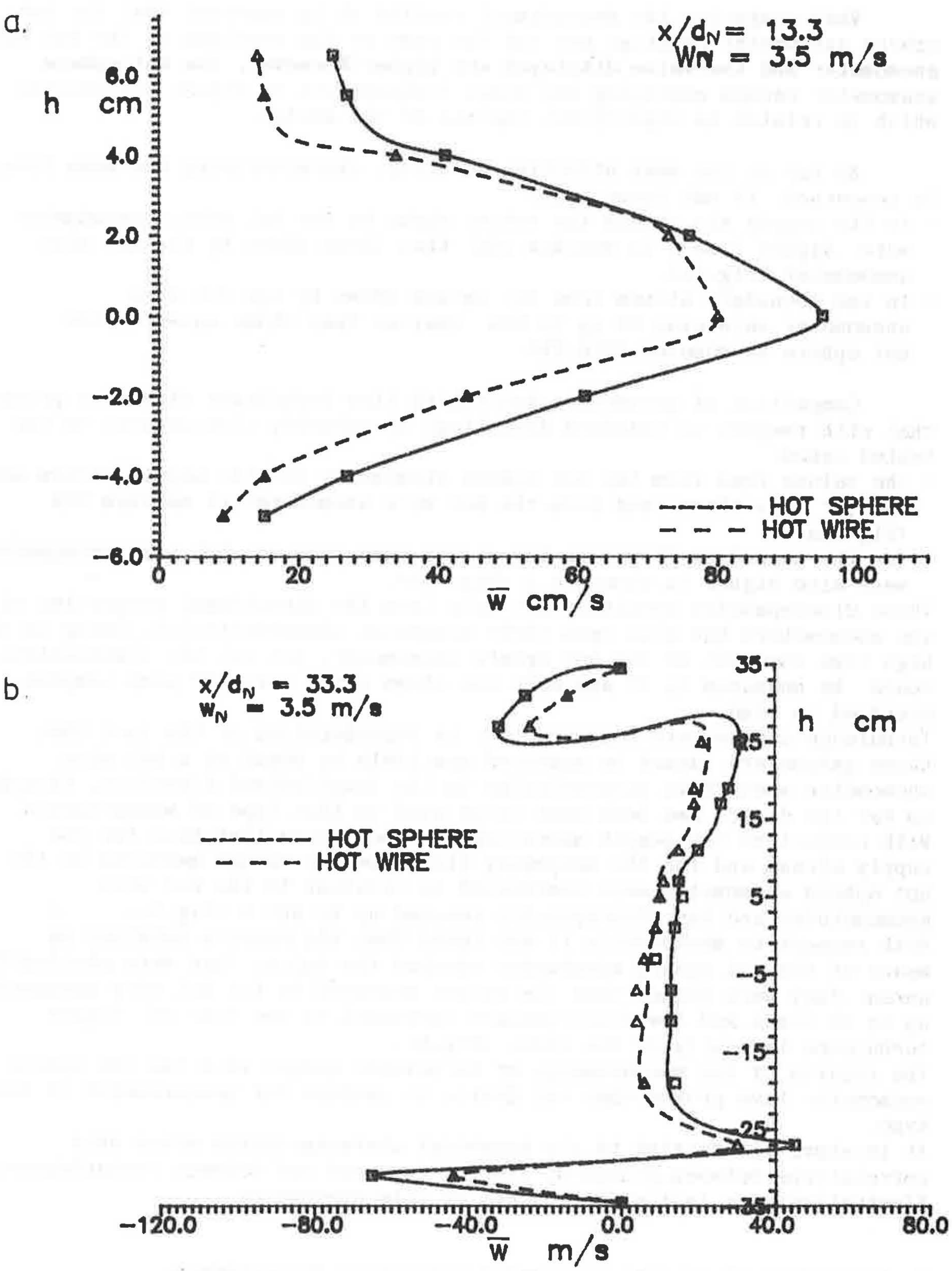
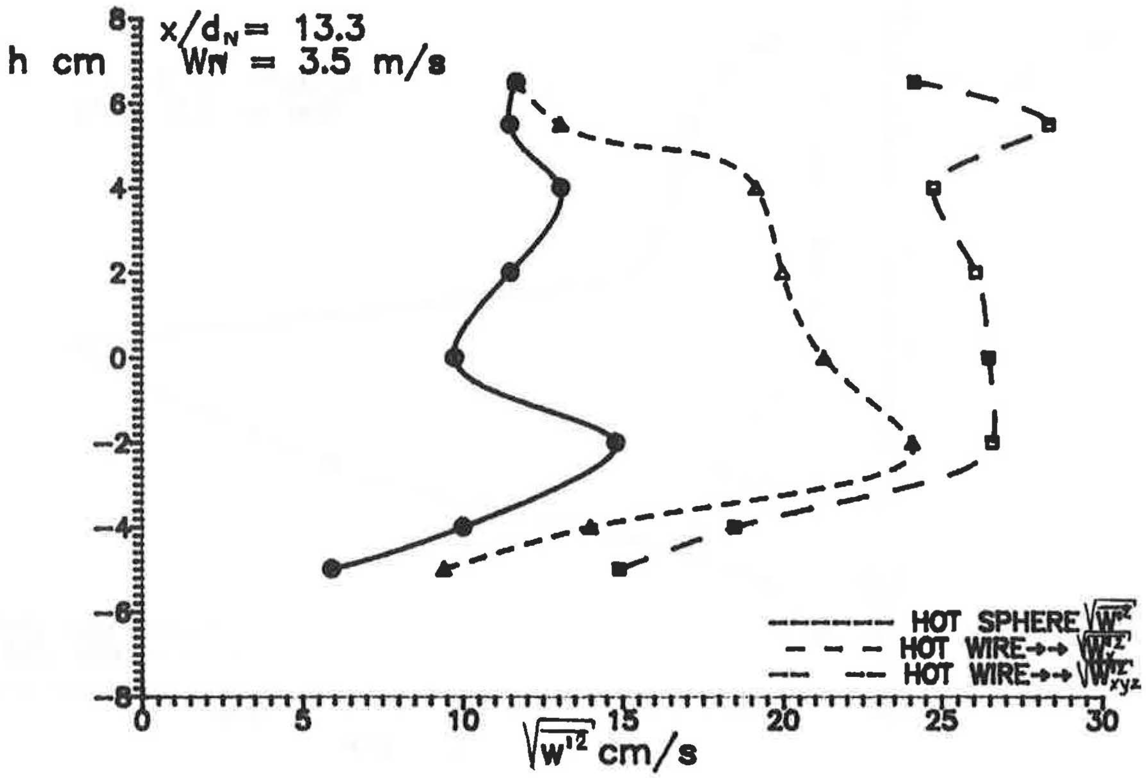


Fig.3. Mean velocity distribution measured with both anemometers when w_N=3.5 m/s

a. in the supply air stream

b. in the secondary flow zone

a.



b.

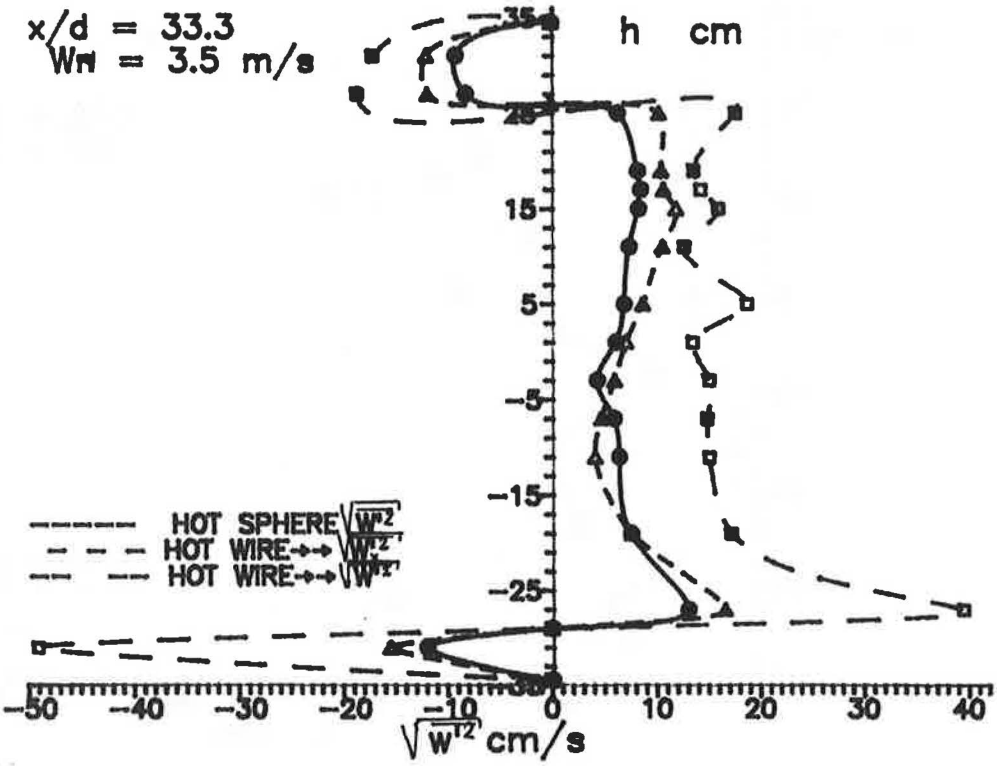


Fig.4. Distribution of standard deviations of velocity fluctuations measured with both anemometers when w_N = 3.5 m/s
a. in the supply air stream
b. in the secondary flow zone

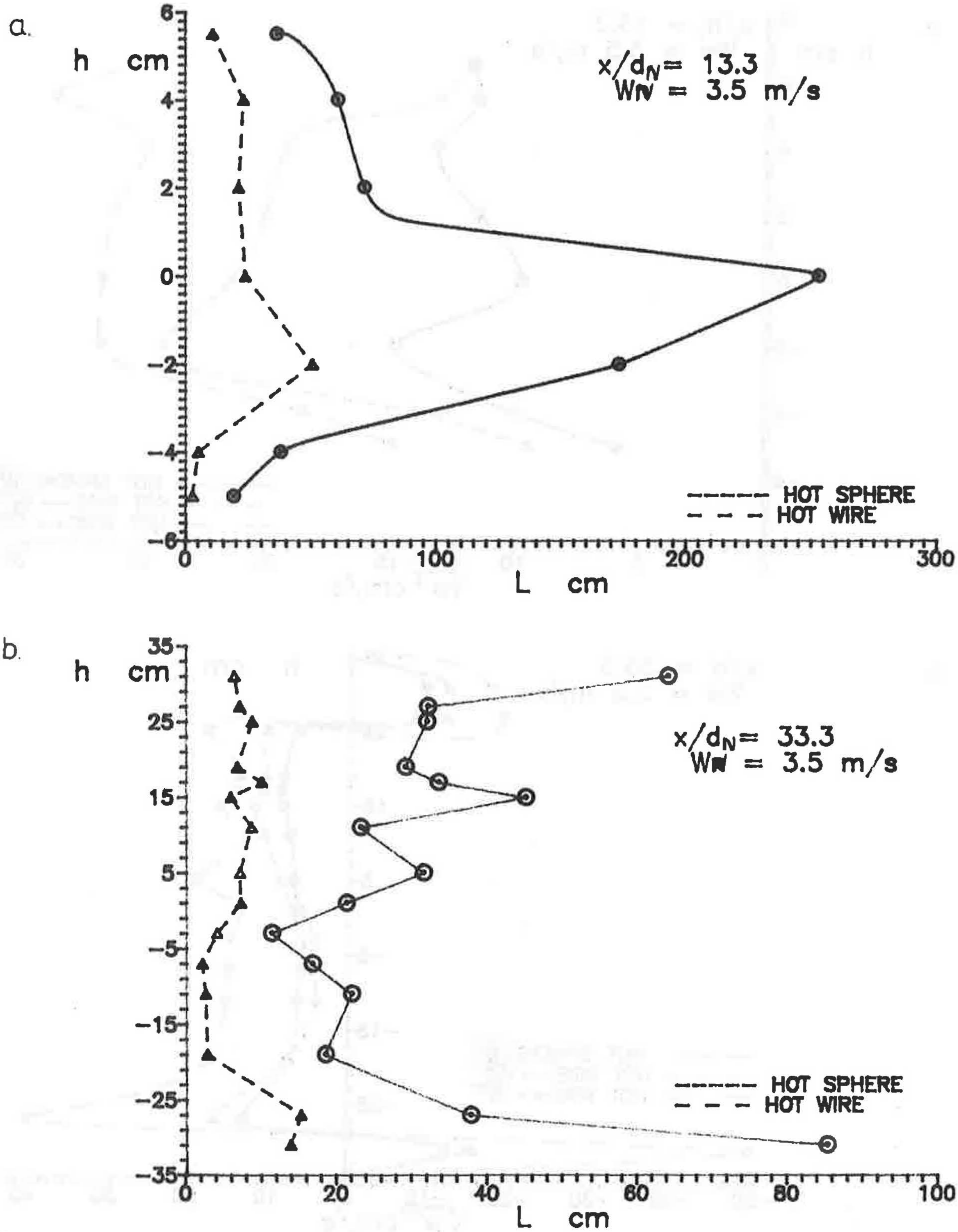


Fig.5. Distribution of the lenght macro-scale measured with both anemometers when w_N = 3.5 m/s
a. in the supply air stream
b. in the secondary flow zone

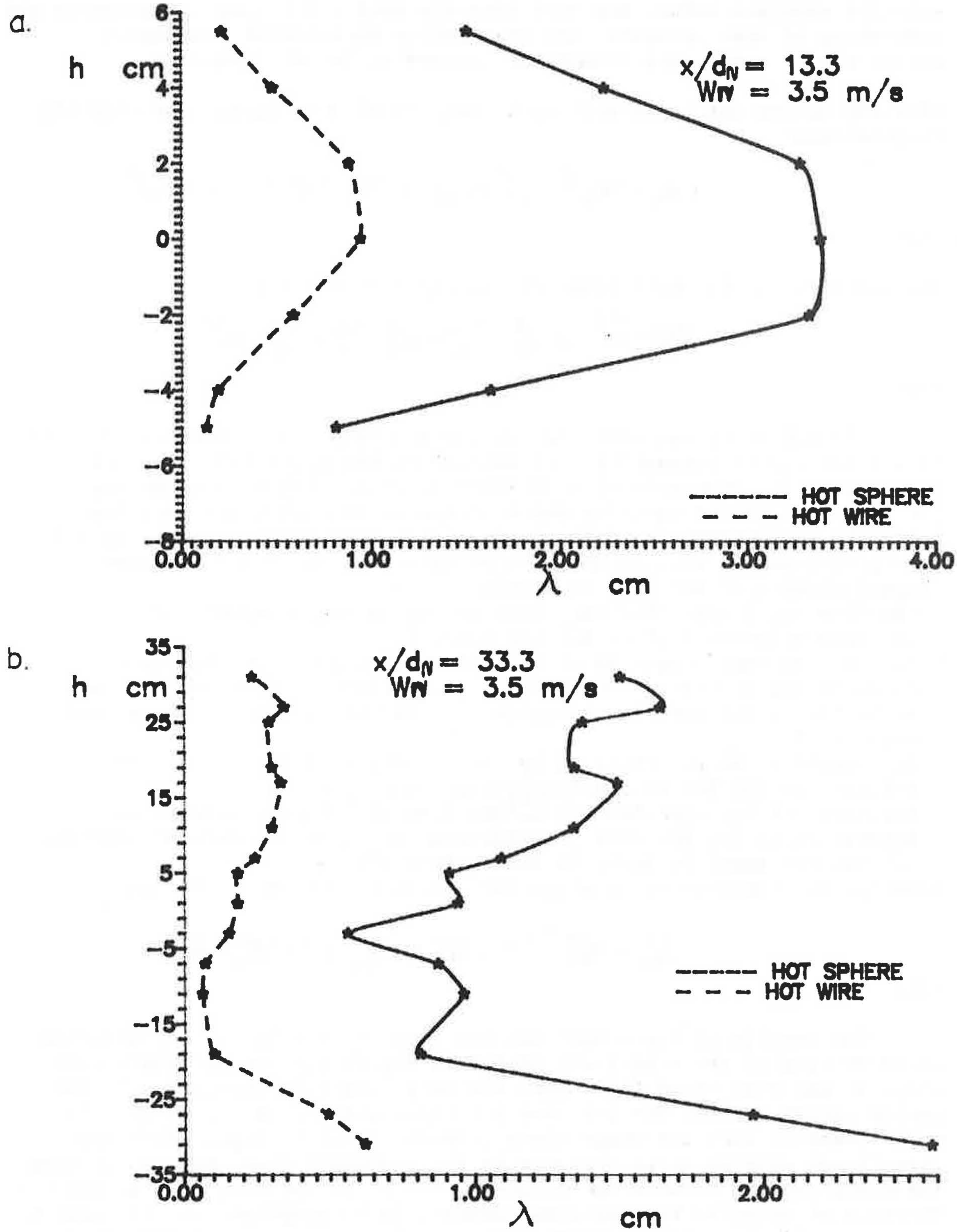


Fig.6. Distribution of the length mikro-scale measured with both anemometers when w_N = 3.5 m/s
a. in the supply air stream
b. in the secondary flow zone

velocity absolute value, measured directly with a hot sphere anemometer and consisting of mean velocity and fluctuation directional components measured with a hot wire anemometer, according to the formula 6.

This expression can be re-written as the sum of mean values and velocity fluctuations:

$$(W_{ef} + W'_{ef})^2 = (\overline{W}_x + W'_x)^2 + (\overline{W}_y + W'_y)^2 + (\overline{W}_z + W'_z)^2$$

(6a)

The averaging of the both sides of the equation yields:

$$\overline{W}_{ef}^2 + \overline{W'^2_{ef}} = \overline{W}_x^2 + \overline{W'^2_x} + \overline{W}_y^2 + \overline{W'^2_y} + \overline{W}_z^2 + \overline{W'^2_z}$$

(10)

The addens on the left side of the equation can be measured directly with a hot sphere anemometer, the addends on the right side have been measured so far precisely or approximately with a hot wire anemometer. The two sides of the equation can be compared to each other when the following assumptions are taken into account with respect to the tested flow properties as well as measurement possibilities and directional characteristics of hot wire anemometer:

- the flow was plane, thus the value of the lateral component of the mean velocity vector, $\overline{w}_y$, was equal 0.
- the longitudinal component of the mean velocity vector, $\overline{w}_x$, to be compared was determined precisely or the effective value of the mean velocity, at hot wire perpendicular to longitudinal direction x, was considered.
- the component $\overline{w}_z$ was replaced by the effective value of the mean velocity at the hot wire perpendicular to z direction.
- variances of the longitudinal $\overline{w_x^2}$and lateral $\overline{w_z^2}$ fluctuations were determined at the hot wire perpendicular to x and z directions whereas $\overline{w_y^2}$ was estimated by means of the formula (7).

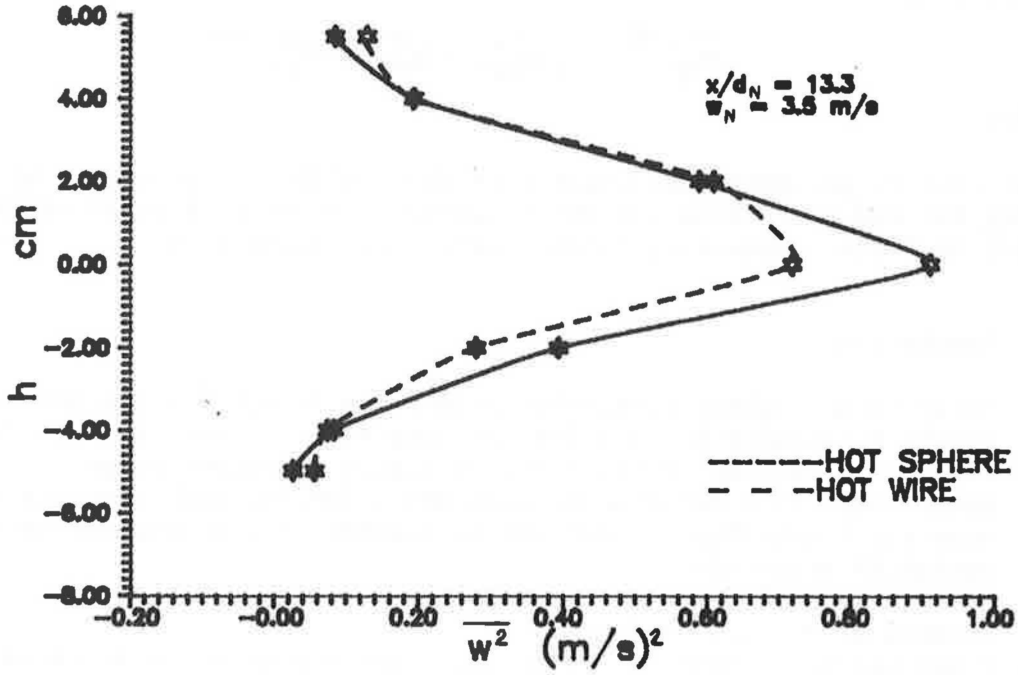
Finally, the comparatory relation (10) could be written as follows:

$$\overline{W}_{ef}^2 + \overline{W'^2_{ef}}^{(s)} = (\overline{W}_x^2 + \overline{W'^2_{x(ef)}} + \overline{W'^2_{y(ef)}} + \overline{W}_{z(ef)}^2 + \overline{W'^2_{z(ef)}})^{(w)}$$

(11)

The results of the comparison are shown in Fig.7a for one selected cross-section of the supply stream and in Fig.7b for the secondary flow zone. It has been found that there are very slight discrepancies in the supply stream between the left and the right side of the equation (11) which confirms that the comparatory interpretation is right. Much more significant discrepancies occuring in the secondary flow zone result from the discrepancies between the effective values of the component $\overline{V}_z$ and the variance of velocity fluctuations, assumed to be compared, and the values in the exact comparatory formula (11). In the secondary flow zone it is difficult to determine the direction of the instantaneous velocity vector and turbulence intensity is higher.
The comparison confirms again that a hot wire anemometer cannot be used for measurements in secondary flow zone.

The standard deviation, measured directly with the hot sphere anemometer, was also compared to the value consisting of the results of a.



b.

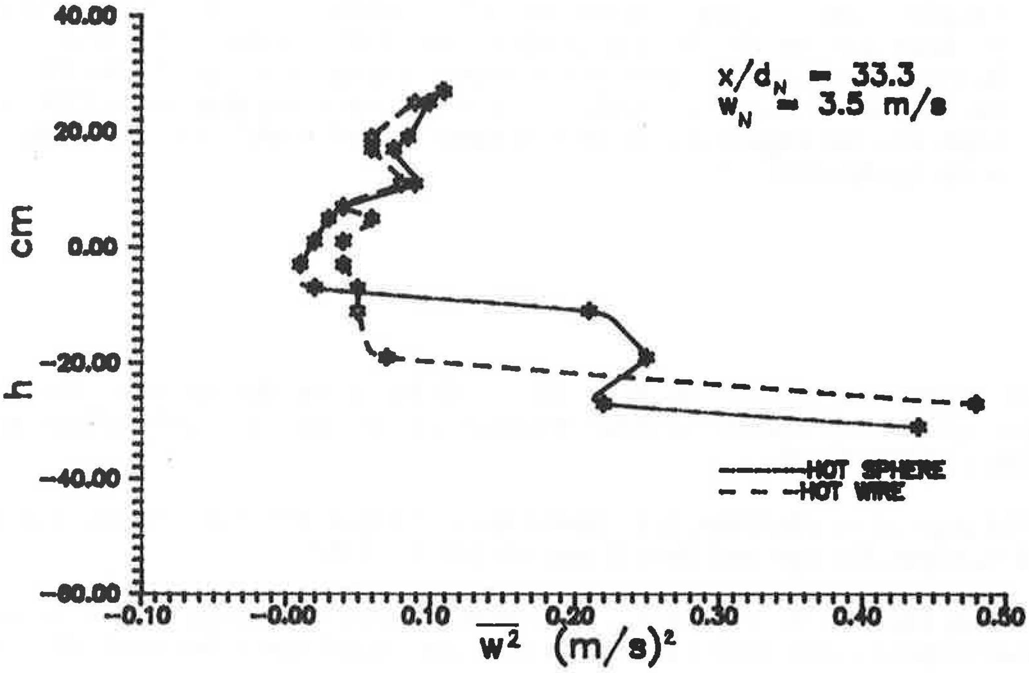


Fig.7. Distribution of the resultant mean-square velocity measured according to conventions for both anemometers when w_N = 3.5 m/s
a. in the supply stream
b. in the secondary flow zone

standard deviation measurements in three directions, by means of the hot wire anemometer:

$$\overline{W_{ef}'^2}^{(s)} = \left(\overline{W_{x(ef)}'^2} + \overline{W_{y(ef)}'^2} + W_{z(ef)}'^2 \right)^{(w)}$$

(12)

The complex parameter was greater in about 150% for the supply air stream (Fig.4a) and about 200% for the secondary flow zone (Fig.4b) which proves that such the comparatory interpretation is purposeless.

8. Conclusions.

1. Owing to hot sphere anemometer properties in ventilation processes, it should preferably be used for measurements of velocity as an element of thermal conditions, particulary in highly turbulent zones.
   Since there is a relation between man's feeling and frequency of air velocity fluctuations, such the anemometer should have adequate dynamical properties.
2. A hot wire anemometer is not suitable for tests of air velocity as an element of thermal conditions.
3. A hot sphere anemometer may be also used for velocity measurements in flows of low turbulence, where the absolute value of mean velocity is close to the longitudinal value of the velocity vector. The inaccuracy may rise up to about 15 %. In particular, it should be pointed out that in flows defined as slightly turbulent e.g. some flows in ducts or supply air streams, there are local areas in which turbulence degree is high and where the inaccuracy may significantly increase.
4. Measurements of turbulence structure parameters, particulary of turbulence scales, by means of a hot sphere anemometer yield the results that are uncomparable to measurement results obtained by means of a hot wire anemometer.

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SUMMARY

Air flows in a two-dimensional supply stream and in the zone of secondary flows were tested by means of a hot sphere anemometer, type HST 1, and a hot wire anemometer, type DISA 55P81. The following parameters were measured: the mean velocity, standard deviation and turbulence scales. The discrepancies of the results were checked for the cases when:

-for low turbulence flows the measuremment convention characteristic of a hot wire anemometer was applied for both the anemometer types

-for high turbulence flows the measurement convention characteristic of a hot sphere anemometer was applied for both the anemometer types

-for low and high turbulence flows measurement and calculation techniques proper for each of the anemometer types were used

It was found that a hot sphere anemometer should preferably be used to measure velocity as an element of thermal conditions of a room whereas in those cases a hot wire anemometer is not suitable. A hot sphere anemometer may also be used to measure velocities of low turbulence flows.