ENHANCEMENT OF HEAT TRANSFER
BY CORONA WIND

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ABSTRACT
The convective heat transfer to or from a solid, can be significantly
enhanced by a nearby corona discharge, through the interaction of the
corona wind with the thermal boundary layer. Experimental measurements
with a number of measuring techniques have shown that this interaction
can be effective because the corona wind flows in quite laminar jets
with a long reach and a small spread.

1. INTRODUCTION
The enhancement of heat transfer across solid-gaseous interfaces by a
nearby corona discharge has been known since 1899 (Chattock). In the
1960's increases of the heat transfer coefficient by about a factor four
above that for natural convection were measured. This resulted in an
intense research on this process throughout the world \(^1,2\). Nowadays
several patents exist on the practical application of this phenomenon.
The heat transfer augmentation process is however, not yet clearly
explained. The corona wind itself, the character of the stream, the
interaction of charged particles with the target object, or a combination
of these factors may be responsible. The aim of this paper is to find
the predominant factors which cause the observed heat transfer enhancement.
New applications of corona wind and an optimization of already existing
apparatus are then possible. Throughout the paper we employ S.I. units.

2. THEORY
In a corona discharge the ionization takes place in a very small region
near the electrode with the smallest radius of curvature. If this
electrode is negative and if an attaching gas is present in the gap,
rapidly drifting negative ions are formed. These ions make frequent
collisions with the neutral molecules, so that they acquire a constant
drift velocity. The force caused by the electric field is then completely transferred to the neutral gas. This is the essential element in the ion drag theory. The flow created in this manner, the so-called corona wind, resembles a jet flow. The body force,

\[ F = \rho_c E, \]  

(1)
in which \( \rho_c \) is the charge density and \( E \) the electric field strength, is a function of the location within the jet flow and acts throughout the entire region between the electrodes. This force couples the electrical and fluid dynamical behaviour of the corona discharge and shows up as a source term in the Navier-Stokes equation. The equations governing the electric, velocity, and temperature field form a large set of coupled partial differential equations. The boundary conditions have a large influence on the nature of the flow field but are often difficult to formulate.

3. EXPERIMENTAL SETUP

The electric wind system as shown in Fig. 1 consists of a flat 90 degree, 1 mm thick brass edge and two parallel stainless steel rods of 5 mm diameter. In this system \( d \) is the distance between the two rods and \( S \) the distance between the point and the plane of the rods. In commercially used electric wind systems of this type (The METC-system, INTER-PROBE Inc., Chicago) a flat plate is placed a distance \( h \) below the rods; this plate may be the heat transfer surface in an oven. We consider the point to be the center of a right handed cartesian coordinate system where the \( x \)-axis is normal to the plane. A negative high voltage is applied to the point. The discharge is a negative corona discharge of the "Trichel-type", in atmospheric air.

4. MEASUREMENTS

Electrical measurements. Figure 2 shows the current drawn to the rods versus the negative voltage applied to the point. The voltage-current characteristic follows the well-known empirical formula:

\[ I_1 = K_1 V(V-V_s). \]  

(2)

\( I \) is the current to the rods, \( V \) is the voltage applied to the point, \( V_s \) is the corona starting voltage and \( K_1 \) is a constant with dimensions \( \text{AV}^{-2} \). When a grounded heat transfer plate is placed some distance below the rods and the current, \( I_2 \), drawn to this surface is measured we observe that:

\[ I_2 \ll I_1 \quad \text{and} \quad I_2 = K_2 (V-V_s). \]  

(3), (4)
$K_2$ is a constant with dimensions $AV^{-1}$. The current $I_2$ is small which indicates that almost all ions reach the grounded rods. This is also confirmed by the hot-wire anemometry measurements.

**Pitot-tube measurements.** The velocity of the corona wind is determined by measuring the pressure difference in accordance with Bernoulli's equation:

$$\Delta p = \frac{1}{2} \rho u^2,$$

(5)

$\Delta p$ is the difference between ambient pressure and stagnation pressure, $\rho$ is the mass density of air and $u$ is the air velocity. The Pitot-tube was placed behind a grounded wire mesh of 59.2% transparency and corrections were made for the disturbances created by this wire mesh.

The measurements show a bell shaped velocity profile with a typical peak air velocity of 4.5 ms$^{-1}$. In the absence of the grounded rods the velocity profile remains bell shaped with in addition a sharp accentuated peak at the center, and lower air velocities.

**Hot-wire anemometry.** Anemometer measurements are based on a measurement of the convective heat-loss from an electrically heated fine wire $\gamma$. Measurements of air velocities down to 0.2 ms$^{-1}$ are possible. The hot-wire anemometry showed a reach of the jet of at least 25 cm for $V = -20$ kV and $S_1 = d = 30$ mm and a relatively small cross section of the jet (typical size 10 cm$^2$) which shows little spreading downstream. The velocity profile as shown in Fig. 3 is bell shaped and the average wind velocity is proportional to the applied voltage $V$ for voltages well above the corona starting voltage $V_s$. Only low frequencies, less than 1 kHz, were present in the anemometer output signal. No significant differences between the readings of a "shielded" and an "unshielded" hot-wire sensor were observed for wire to rod distances greater than the rod to rod spacing $d$. The grounded shielding devices for the hot-wire sensor should divert charged particles away from the wire. An additional test was to measure the current drawn by an unshielded hot-wire sensor placed at a distance less than $d$ below the plane of the rods; even then its current was less than 0.05 $\mu$A. This confirms that most of the ions flow to the two grounded rods.

**Schlieren diagnostics.** A Schlieren setup provides an optical visualization technique in which the intensity of the transmitted light depends on the gradient of the air density $\beta$. In our experiments we had to heat the corona electrode to generate the necessary air density variations. Photograph 1 shows a Schlieren picture of a corona wind jet. The photograph shows a stable flow pattern; the actual jet is wider than is shown in the picture,
because the hot air coming from the heated point is concentrated in the center of the jet.

**Artificial mist.** We also used a mist produced by solid CO₂ to visualize the air flow in an electric wind system. Photograph 2 shows a picture where the mist is introduced downward into the electric wind system through 11 small holes in the wall of a tube parallel to the rods. From the artificial mist experiments we obtained the following conclusions:
- the velocity profile has a small diameter (≈ 35 mm)
- the flow is stationary within two seconds after the application of the negative high voltage.
- the generated jet has a much more laminar character than a jet originating from an orifice.

This last conclusion is in full agreement with the results from Schlieren and anemometer measurements. A difficulty in the comparison of an "orifice jet" and a corona wind jet is the question which parameter should be the same in both jets. Nevertheless the conclusion is quite general, since a longer reach, a smaller spread and a lower turbulence was seen in all measurements on corona wind jets.

**Heat transfer measurements.** Figure 4 shows some results of heat transfer measurements on a heated horizontal copper plate with dimensions 220 x 170 mm. The electric wind system used here consists of 75 discharge points as in Fig. 1, arranged in five rows of 15 teeth parallel to the rods. The temperature rise ∆T with a heating input of 44 W decreases by a factor two after the electric wind system has been energized. The electric power input to the corona discharge is 5.4 W. This observed increase in the heat transfer coefficient is in this case only a factor two, because the free natural convection upward from the horizontal plate is appreciable.

Preliminary optimization with respect to the parameter d shows that maximum heat transfer takes place for d ≈ 25 mm, for S₁ = 33 mm. The other parameters S₁ and h have only a weak influence on the heat transfer.

5. **DISCUSSION AND CONCLUSIONS**

A jet generated in an electric wind system is more laminar, spreads less and has a longer reach than a jet originating from an orifice. The reason for this is that the smoothly distributed body force acting in the corona wind generates much less initial disturbance than a sharp edge at the end of the tube in the case of an orifice jet. The conclusion must be that the enhancement of heat transfer is caused by the more laminar character and
the longer reach of the corona wind jet. The negative ions cannot con-
tribute significantly to the heat transfer since very few ions reach the
heat transfer surface.

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Fig. 1 Electric wind system.

Fig. 2 Current versus applied voltage; $S_1 = d = 30$ mm and $h = 60$ mm.

Fig. 3 Average wind velocity versus the $y$ and $z$ coordinates; $S_1 = d = h = 30$ mm, $V = -16$ kV.

Fig. 4 Temperature rise of a horizontal metal plate after the heating elements have been switched on; with and without the corona wind. $S_1 = 33$ mm, $d = 25$ mm, $h = 40$ mm and $V = -120$ kV.

Photograph 1, Schlieren picture of corona wind, originating from a heated point. $S_1 = 15$ mm, $d = 27$ mm and $V = -18$ kV.

Photograph 2, Corona wind influencing artificial mist trails. $S_1 = d = 30$ mm and $V = -20$ kV (steady state). Note the discharge point in the top center.