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ELECTROSTATIC EFFECTS OF CHARGED STEAM JETS

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SUMMARY

The electrostatic charging of wet steam during an expansion process yields a charged jet that interacts with the environment. The generation and distribution of the volume charge density in the stationary state determines the electrical field strength in the vicinity of the jet. As a consequence of drop evaporation a discharging drift current is generated. Resulting electrostatic ignition hazards and adequate safety measures are examined in more detail in connection with the charged state of a jet.

INTRODUCTION

The free jet expansion of steam during operational processes and the accidental release of steam from plants is a frequent process in chemical and other industries. For a long time it has been known that wet steam expansion is partially connected with a high electrostatic charging, a fact to be considered in zones with flammable atmospheres and which causes technological interference (ref. 1). Results of Napier (ref. 2), Seifert et al. (ref. 3) and Jones et al. (ref. 4) show that some expansion processes of wet steam yield a real ignition hazard if no safety measures are considered. These results cannot be transfered to other expansion processes with other parameters, so no useful conclusions can be drawn with reference to the charge accumulations and discharges. The processes within the free jet and in its vicinity claim therefore especial interest since the charge transfer and the field influence directly cause the generation of ignition sources and other interference.
The charged particles dispersed in a gaseous media (air and steam) are an electrogasdynamic system that essentially consists of water ions and charged water droplets. When the impulse of the two-phase jet decreases and the drops evaporate near the jet contour depending on the air humidity, the charges flow to earth. Using some of the properties of a turbulent free jet, e.g. the velocity distribution and the characteristic jet geometry it is possible to conclude in a half-empirical way useful results regarding the charge and field strength distribution. A satisfying theoretical solution to this problem is difficult to reach since a strong coupling exists between charge movement and electric field, as in the case of the known DCHV corona problem. The essential processes in the electrogasdynamic two-phase system are not only relevant for

the water-steam combination occuring here, they have a general significance for the expansion of other two-phase systems with gaseous and liquid components. So one can expect similar behaviour in such systems.

The generation of electrostatic hazards as a result of the free jet expansion was earlier considered only from the viewpoint of a field influence on neighbouring conductors which yields brush or spark discharges respectively, depending on the charging of the orifice or the impinging and charging of plant parts. The charging process by drift currents resulting in an ignition hazard was insufficiently taken into account. For the avoidance of a hazardous charging of wet steam and the prevention of a charge accumulation resulting eventually in incendive discharges such means are necessary which are also in practice useful.

EXPERIMENTAL

The experiments were carried out on horizontally and vertically oriented steam jets where the material of the piping andorifices was steel. Contrary to the above cited investigations, special attention was put on the constancy of the values of thermodynamic quantities determining wet steam. The quantities were the steam content x and the pressure p corresponding to the Mollier enthalpy-entropy diagram. The velocity of the steam released in the discharge opening or immediately after it was calculated with the equations which are valid for supercritical or subcritical escape of steam (ref. 5). An additional experimental estimation was carried out. The measurements were made by use of two ring-shaped induction probes which allow the measurement of the velocity and the volume charge. The probes were constructed following the charge measurement method proposed by Gajewski (ref. 6). Further measurements were made with a Prandtl tube and a mechanical anemometer. The examined orifices were pipes, specially designed nozzles and slits as they appear at leaky flange gaskets. During the release process the excess charge of the jet was calculated by means of current measurements from the electrically insulated orifice or from the releasing pipe. Field strength measurements were carried out with a static and a dynamical fieldmeter. The drift current was measured by a probe connected to a charge integrator.

THEORETICAL

The theoretical considerations are based on a simple jet model. Figure 1 shows its characteristics.

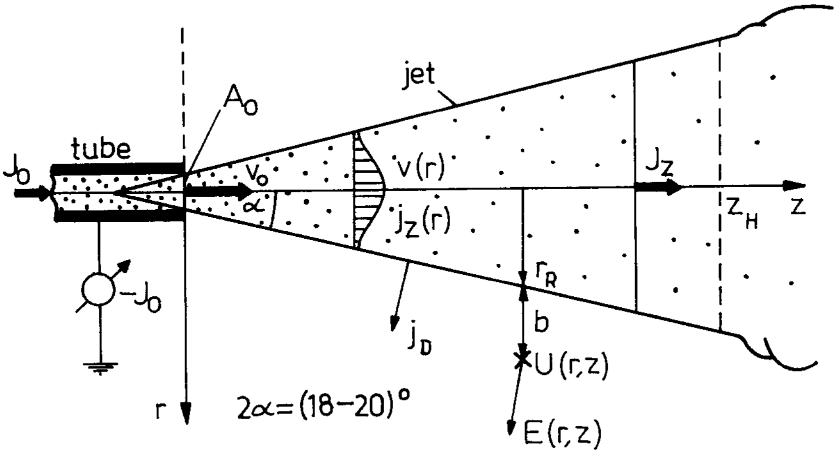

Fig. 1. Simplified stationary model of a two-phase jet containing charged water particles.

The potential U of a point P(r,z) is given by

$$U = 1/(4\pi\cdot\varepsilon_0\cdot\varepsilon)\ \int_V (\rho/r')dV \tag{1}$$

where ρ = volume charge density, ε_0 and ε = absolute and relative permittivity, r' = distance between an elementary volume charge and point P. U was approximately calculated by the numerical integration of equation 1 using defined distributions for ρ. If the released charges stay within the jet for every cross-section the constancy of I_z is fulfilled

$$I_z = I_0 = \int_A j(r,z)dA = \text{const.} \tag{2}$$

Then the volume charge density is

$$\rho(r,z) = j/v = \text{const} \tag{3}$$

since j and v are connected with the same particles and have also the same cross-sectional distribution. Under these conditions the Poisson equation describing this problem is soluble. However a comparison with measurements showed that a constant charge density did not exist. So a charge decreasing mechanism was taken into account. Along the way dz the current I_z in a cross-section varies by dI_z. This could be caused by a leakage current $I'_v = n' I_z$ with $0 \leq n' \leq 1$. The balance gives

$dI_z/dz + n' I_z = 0$

and therefore

$$I_z = I(z) = I_o \exp(-nz). \qquad (4)$$

This simple model is consistent with a charge density depending on z by the relation

$$\rho \sim \exp(-nz) \sim 1/(1+nz+(nz/2)^2+\ldots)$$

The measured and calculated field strengths are in accordance with this result. The charge decreasing mechanism essentially consists of the appearance of a drift current of evaporated liquid particles from the outer jet regions ($v \approx 0$). Under the influence of the field the generated ions move depending on their mobility along the field lines to earth. In the jet a current difference arises between I_o and I_z which is equal to the leakage current I_D.

$$I_D = I_o - I_z = I_o - \int_A j(r,z)dA,$$

$$I_D = I_o - 2\pi \int_0^{r_R} rv\rho \ dr. \qquad (5)$$

Knowing v and ρ the assessment of I_D and of a mean value for the drift current density $\bar{j}_D$ is possible.

RESULTS

Charge generation

The flow of superheated steam in an pipe and its expansion into a free space cause only a small electrification. In this case the charge carriers are connected with transported salt, rust and other particles. A charge generation resulting in electrostatic ignition hazards is to be expected only during the wet steam expansion.

Wet steam contains a lot of liquid particles and the type of flow varies between spray flow and annular spray flow. Figure 2 shows the measured dependence of the charging current I_o flowing from the insulated orifice to the ground and the pressure p_u and the steam content x (ref. 7). It is obviously that the empirical condition $p_u x \leq 0.15$ MPa guarantees a charging current of only $I_o \approx 1 \mu A$. Below a pressure of $p_u = 0.14$ MPa there are no hazardous charge accumulations to be expected.

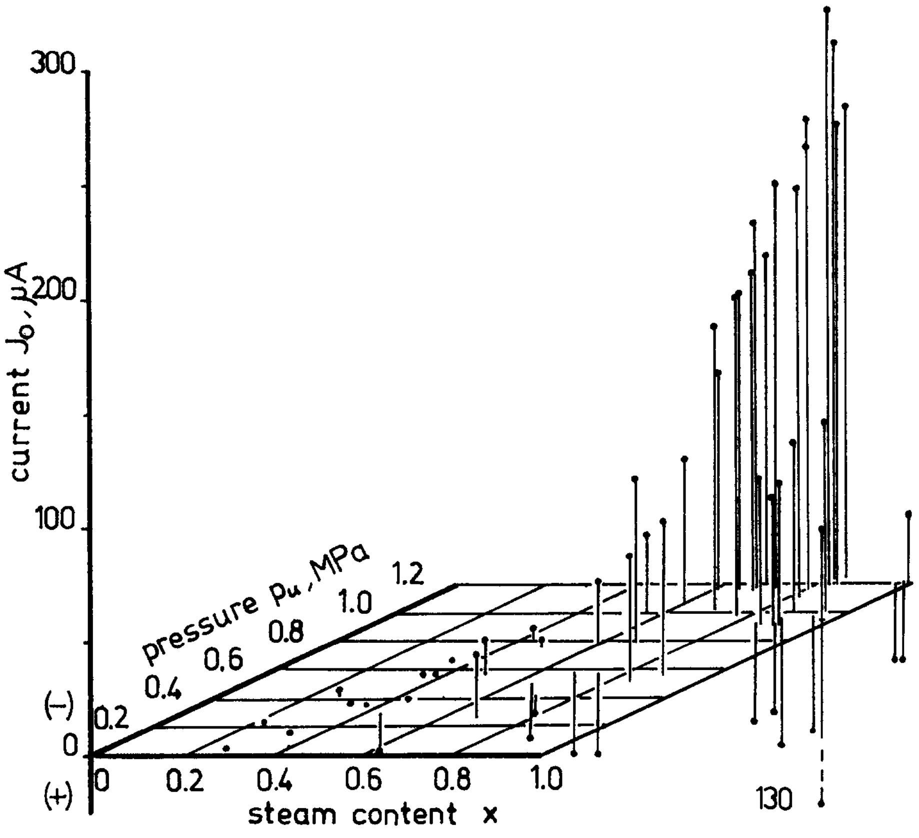

Fig.2. Charging current I_0 during free jet expansion of wet steam dependent on the steam content x and the pressure p_u, orifice: steel piping (Internal diameter d_i = 50 mm).

The results in figure 2 are also valid for pipes with smaller diameters. However below an internal diameter of d_i = 10 mm a light increasing of the electrification exists for steam escaping with very low steam content. This is consistent with results for escaping steam from narrow slits. In these cases the wet steam is very highly charged. It is possible to define an initial volume charge density $\rho_0 = I_0/(A_0 \cdot v_0)$, where A_0 = cross-sectional area of the jet near the orifice, v_0 = corresponding jet velocity. Following maximal values were measured: $\rho_0 = (5...10) \cdot 10^{-4}$ C/m^3 for expansions from a leaky tube flange (piping with d_i = 50 mm) at p_u = 1.0 MPa, $\rho_0 = (1...10) \cdot 10^{-5}$ C/m^3 for expansions from steel and rubber piping (10 mm $\leq d_i \leq$ 50 mm). These values surpass earlier reported results (ref. 2).

Field strength

In the vicinity of a charged steam jet the electric field strength is defined only by the resulting volume charge density and the surrounding conducting bodies. The aperture angle of such a jet in its initial part is approximately 18 to 20 degrees and depends little on the pressure and type of orifice. The considered jet length z_H is represented only by that part of the jet possessing the typical conic shape. Field strength measurements close to the jet are influenced by the inevitable field distortions and only a field meter position close to the conducting surroundings guarantees a correct measurement. In geometrically simple cases a computable correction of the measured values is possible. Such corrections were carried out with the values presented. In figure 3 measured field strengths are given for two horizontal steam jets with different initial charge densities and "electrical" jet lengths z_H. The field strength was measured with a constant distance to the jet contour. Curves 1' and 2' in figure 3 represent the calculated field strengths according to the above explained calculations. A function of the type

$$\rho = \rho_0 (1+z)^{-n} \qquad (6)$$

was used to get an axial charge density distribution for the field computation.

The calculated and measured values do agree sufficiently. Curve 3 gives the calculated field strengths for the expansion of a jet with a weak impulse but with an intense electrification as is typical of a steam jet from a leaky flange. Because of the short jet length z_H a comparatively high charge concentration took place resulting in high field strengths and drift currents. A measurement was not possible so only one value is presented. The field strengths in figure 3 cannot be compared with the results of other authors since the experimental conditions were too different. Seifert et al. (ref. 3) measured values close to a steam curtain in the range of (5...9) kV/cm. However the influence of field distortions was unknown and the geometry of the space charge cloud was not the same as in the present work. The order of magnitude of the measured values in figure 3 was also 10 kV/cm without any corrections.

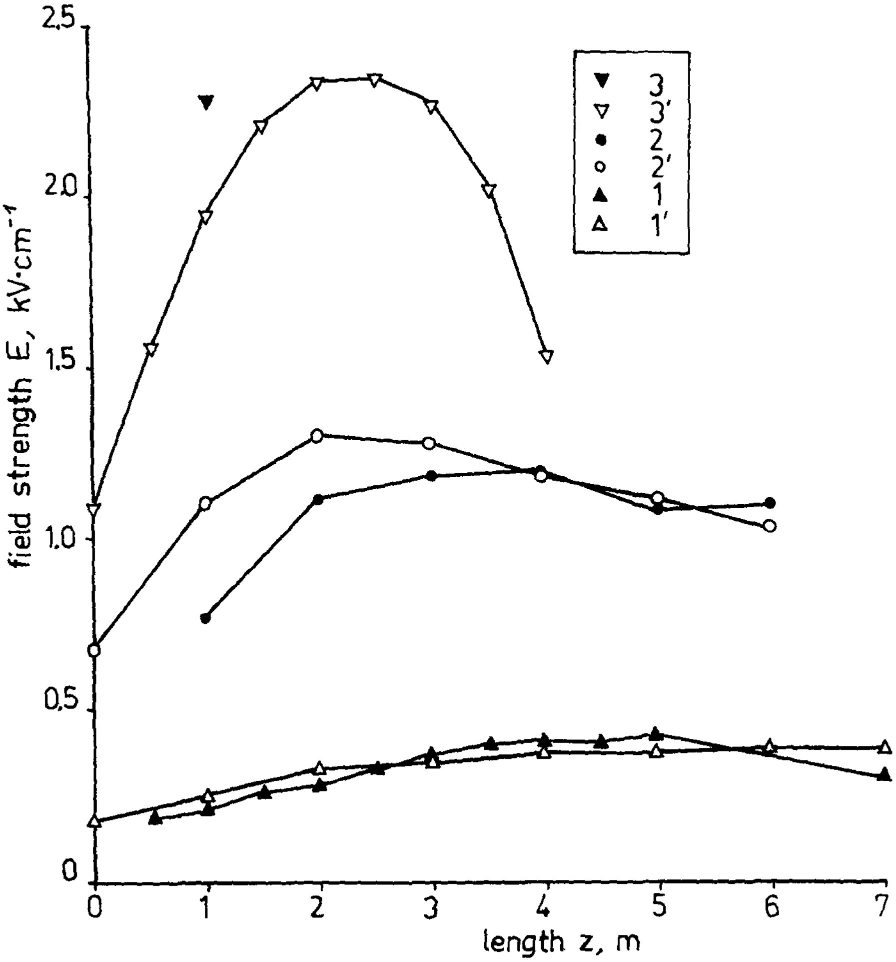

Fig.3. Measured (1,2,3) and calculated (1',2',3') field strengths E,
1:pipe with d_i = 50mm, p_u = 1.1MPa, ρ_0 = 23.4 $\mu C/m^3$, b = 1m, n = 1.5, z_H = 10m,
2:pipe with d_i = 24mm, p_u = 0.25MPa, ρ_0 = 129 $\mu C/m^3$, b = 0.5m, n = 2, z_H = 8m,
3:leaky flange gasket (piping with d_i = 50mm), p_u = 0.4MPa, ρ_0 = 317 $\mu C/m^3$, b = 0.5m, n = 2, z_H = 4m,
b = distance to jet boundary .

Drift currents

If the charge distribution in the steam jet is known an assessment of the current I_D produced can be made supposing a velocity distribution following equation 5. The investigated two-phase jets had an axial distribution of the velocity corresponding to

$$v\ (z) = c_v(a+z)^{-m},$$

where a, c_v and m are constants. The transversal distribution followed the known exponential relation. With equation 5 we get

$$I_D = I_o - \left[\frac{\pi \cdot \varrho_o \cdot c_v \cdot (1+z)^{-n}}{k_1}\right] \qquad (7)$$

where k_1 = normalizing factor. I_D represents the current flowing off between z = 0 and z. Figure 4 shows the increase of I_D and the decrease of I_z with z for those jets as in figure 3. If I_D flows steadily through the conical jet surface a mean drift current density $\bar{j}_D$ = 0.20nA/cm² respectively $\bar{j}_D$ = 0.15nA/cm² follows from figure 4.

Experimental measurements gave $\bar{j}_D$ = (0.2...0.5)nA/cm².

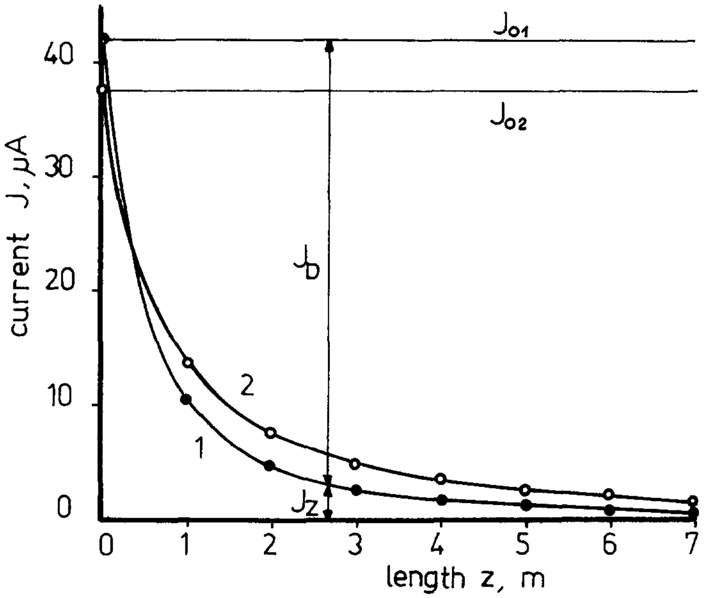

Fig.4. Calculated drift currents I_D and the corresponding current I_z along the jet axis, expansion conditions as in fig.3.

The measurements of the drift currents close to the jet are influenced by field distortions and discharges. Therefore only the range of measured values is given. The drift current starts at the jet boundary and its magnitude also depends on the difference between the actual and the saturation vapour pressure of water in the ambient air. A strong reduction of I_D takes place if the relative humidity reaches values of greater than 95 per cent. This is connected with an increasing "electrical" jet length and a reduced decay of the axial volume charge density.

HAZARDS AND SAFETY MEASURES

Spark discharges

An ignitable spark discharge in the area of the electric field influence of a charged jet requires a sufficiently charged conductor. Other conditions such as a minimal capacity and the energy of the discharge are stressed in other papers (ref. 8). The charge accumulation on a conductor can be the result of the induction caused by a charged steam jet. Field strengths guaranteing such an effect at distances of some meters can be reached during the above mentioned expansion processes. However this charging is not very likely since the necessary change between insulation, grounding and approximation of a second conductor is difficult to perform in practice. The charging of insulated conductors by drift currents to a level initiating spark discharges in the insulation path is possible. The metallic covers of thermal piping insulations are an example. In the same manner also a person with insulated shoes is chargeable. It was deduced by examining cases that a distance of $\geqq$ 3 meters to the contour of a steam jet is sufficient to avoid hazardous charge accumulation under operational conditions. A greater distance is needed if no further conductors are present in the vicinity of the jet.

Brush discharges

In nearly all examined cases it was impossible to ignite a stoichiometric mixture of hydrogen/air by brush discharges between the jet and a spherical electrode with a diameter of 18 mm.
Only very seldom with a steam jet from a leaky tube flange can the possibility of ignition exist. The high flow velocity around the electrode and the influence of the drift current prevents, in most cases, the possibility of ignition. A charge decrease in the jet or a decrease of the charge generation eliminates the described hazardous effects. Besides the already mentioned safety measures such as pressure limitation, grounding within defined safety distances and the use of passive ionizators in the initial part of the jet discharge it to a safe level. A reduction of the generated charges in the orifice is achievable by an orifice with a diaphragm (ref. 7).

CONCLUSION

The expansion of wet steam from orifices results in an electrification of the escaping jet. The charge is generated during partial disruption of the surface of water films (resulting in negative particles) and water droplets (resulting in positive particles) as the steam leaves the orifice. Little charge occurs during pipeline flow. In the constant geometric conditions of the piping and orifice the charge of the jet is only dependent on the steam content and the pressure or temperature of the wet steam. The electrical field strength in the vicinity of the jet is computable by means of the volume charge density in the stationary state. The charge density is reduced along the jet axis by evaporating droplets forming a drift current towards earth. A relation of the type $\rho \sim (c+z)^{-n}$ with c,n = constants describes the decay of the charge density ρ along the jet axis. The ions produced form a drift current discharging the jet. In practical cases the obtained values of the mean drift current densities are in the order of 10^{-1}nA/cm^2 at the jet boundary. Owing to the influence of the electric field and the drift current, ignition hazards and technological interference arise in the enviroment. Prevention is possible by:

(1) earthing of neighboured conductors at all times
(2) eliminating risk from discharges from steam itself by
(a) pressure limitation or (b) specially
designed orifices or (c) ionizators.

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