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# The use of chimney flow as a jet-pump to reduce emissions concentrations

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## *ABSTRACT*

The paper describes a procedure to design an outer stack around an existing stack in order to reduce the concentrations of emissions. The procedure outlined treats the inner and outer stacks as a jet-pump (sometimes called an ejector or injector). The primary flow from the inner stack draws in clean secondary flow which mixes with the primary flow, thus reducing the emissions concentrations, but clearly not the mass flow of the emissions. The procedures have been used for the design of two outer stacks, and measurements have shown that the performance is roughly as expected. The method apparently exploits a loophole in regulations which specifies a concentration level which must not be exceeded, not a mass flow rate.

## *INTRODUCTION*

This paper details the sizing of outer stacks to be located around existing stacks of a milk powder drying facility to attempt to reduce the concentration of solids emissions from these stacks back to within their prescribed maximum solids concentration of 250 mg / m$^3$ at NTP. The idea behind this design is that the primary flow from the inner exhaust stack would induce a secondary flow in the annular region between it and the outer stack. The two flows would then mix in the downstream region enclosed by the outer exhaust stack. Since the entrained flow is "clean air", the mixed flow would have a lower concentration of solids.

## *ANALYSIS*

The required design was reduced to a simplified model, which was then analysed using standard fluid flow equations. The geometry analysed and the nomenclature used is given in Fig. 1.

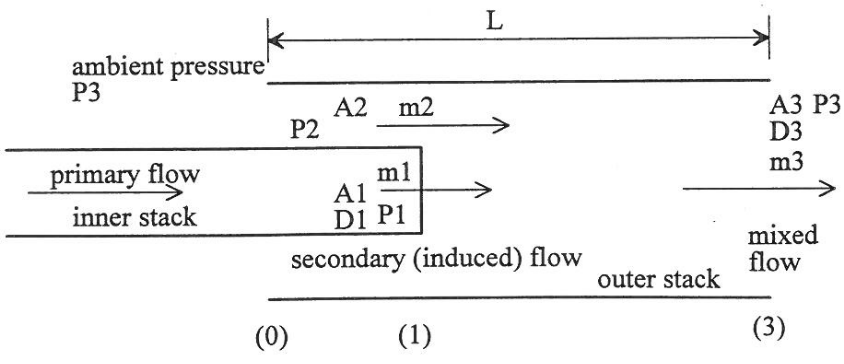

Fig. 1 Schematic diagram of geometry analysed

In Fig. 1 it can be seen that if the thickness of the secondary stack is thin compared to the gap between stacks then

$$A_3 = A_1 + A_2 \tag{1}$$

where $A$ is cross-sectional area in m$^2$. Also from continuity it follows that

$$\dot{m}_3 = \dot{m}_1 + \dot{m}_2 \qquad (2)$$

where $\dot{m}$ is mass flow rate in kg / s.

We can determine the resulting flow by applying the momentum equation between stations (1) and (3), and by using the energy equation between the inlet to the outer stack, station (0), and the inlet to the mixing region station (1). This enables a relationship between the pressure and velocity of the secondary flow to be obtained.

The Momentum Equation between stations (1) and (3) can be written:

$$P_1A_1 + P_2A_2 - P_3A_3 - (\tau\pi D_3 L) = \dot{m}_3V_3 - \dot{m}_1V_1 - \dot{m}V_2. \qquad (3)$$

The bracketed term on the left hand side is the contribution from the shear stress acting on the surface of the secondary duct between stations (1) and (3). It can readily be shown that this term is small for a smooth duct, and so it has subsequently been assumed to be equal to zero.

We also make the assumption that the streamlines in the region at the end of the inner stack are straight and parallel. This means that the pressures $P_1$ and $P_2$ are the same. Furthermore, the static pressure at the outlet of the outer stack is the same as the ambient pressure $P_3$. Since the secondary flow has to be induced through the annular gap, it follows that the pressure at station (1), i.e. $P_1$ and $P_2$ must both be lower than $P_3$. With these assumptions, equation (3) reduces to

$$(P_1 - P_3)(A_1 + A_2) = (\dot{m}_1 + \dot{m}_2)\left(\frac{\dot{m}_1+\dot{m}_2}{\rho_3 A_3}\right) - \dot{m}_1\left(\frac{\dot{m}_1}{\rho_1 A_1}\right) - \dot{m}_2\left(\frac{\dot{m}_2}{\rho_2 A_2}\right) \qquad (4)$$

In the case where the temperatures of the primary and secondary flows are different, meaning that the densities are different, it is difficult to simplify equation (4) into anything very manageable. However, to gain some insight, it is of interest to take the special case where the fluids and the temperatures are the same, and thus the densities $\rho_1$, $\rho_2$ and $\rho_3$ are the same. Equation (4) can then be reduced to:

$$(P_3 - P_1)(A_1 + A_2)^2 = \rho A_1 A_2 (V_1 - V_2)^2 \qquad (5)$$

The secondary flow starts from rest and has to be drawn into the annular gap, and there is an inlet loss factor, $k_i$, associated with station (0). The Energy Equation between (0) and (1) can thus be written:

$$P_3 = P_2 + q_2 + k_i q_2 \qquad (6)$$

where $q_2 = \frac{1}{2}\rho V_2^2$ is the dynamic pressure of the flow in the annular gap. Substituting $P_1 = P_2$ and for $q_2$ in (3) results in:

$$(P_3 - P_1) = \tfrac{1}{2}\rho V_2^2 (1 + k_i) \quad . \qquad (7)$$

Combining (5) and (7), and writing $R$ for the area ratio $A_2 / A_1$ results in:

$$\frac{\dot{m}_2}{\dot{m}_1} = \frac{R}{\sqrt{\frac{R(1+k_i)}{2}(1+R)+1}} \qquad (8)$$

A more detailed analysis with a high temperature primary flow showed that equation (8) was slightly conservative. It is believed that this is the case because the higher temperature stream will have a higher speed than used in (8) because of its lower density. This higher speed stream is better at entraining the secondary flow than a lower speed stream. Equation (8) is thus suitable for design.

The length of the outer duct is determined on the basis of having sufficient length for the inner jet flow to completely mix with the entrained flow. The author did not find much relevant information on concentric mixing jets in the short time he looked. The most useful information was that on jets issuing into stationary fluid (ref. 1), which of course is different from the present case where there is a secondary stack around the mixing flows.

For the case of circular turbulent jets, it has been found that the jet width expands in a linear fashion with distance, and the half angle of the jet is about 12 degrees. Note however, that the speed of the jet at the edge is very low. It has also been found that the half angle to the part of the jet where the speed is half of the maximum is about 5 degrees. This is a much shallower angle, and requires an outer stack of relatively large length compared to its diameter.

On the basis of this information, the present designs were based on a jet expansion angle of about 6 degrees. The overlap length was based on having a length of about three gap-widths.

## APPLICATION TO PRESENT DESIGNS

Using the procedures given above and the existing stack geometries and data in the following table, the outer stack diameters and lengths were calculated. The aim was to get the concentration of particulate matter to below 250 mg / m$^3$.

| **flow parameters** | Stack 1 | Stack 2 |
|---|---|---|
| Stack diameter at sampling plane | 1.28 | 0.45 |
| average velocity | 13 | 10.3 |
| average temperature, deg C | 88 | 37 |
| flow rate at discharge conditions, m$^3$ / min | 1,002 | 98 |
| flow rate at dry NTP conditions, m$^3$ / min | 728 | 85 |
| **particulate matter** | | |
| concentration, mg / m$^3$ , at NTP | 440 | 270 |
| mass rate g / min | 320 | 23 |

Stack One

$D_1$ = 1.28m, and it is necessary to reduce the concentration from 440 to about half, say 220 mg / m$^3$. This means that

$\dot{m}_3/\dot{m}_1 = 2$, and so $\dot{m}_2/\dot{m}_1 = 1$.

Using equation (8) with $k_i = 0.5$, this mass flow rate ratio requires an area ratio, R in excess of 3, say 3.2, and so $D_3 / D_1 = (1 + 3.2)^{0.5}$.
The inside diameter of the outer stack therefore becomes $D_3 = 2.62$ m.

Stack Two

$D_1 = 0.45$, and it is necessary to reduce the concentration from 270 to say 200 mg / m$^3$ to again be conservative. This means that

$\dot{m}_3/\dot{m}_1 = 270/200 = 1.35$, and so $\dot{m}_2/\dot{m}_1 = 0.35$, say 0.4.

Using equation (8), this mass flow rate ratio requires an area ratio, R, of about 1.2, and so $D_3 / D_1 = (1 + 1.2)^{0.5}$.
The inside diameter of the outer stack therefore becomes $D_3 = 0.7$ m.

The outer stack lengths are based on a jet divergence half angle of about 6 degrees, rounded up to suitable values. The pertinent dimensions are given in the schematic diagram below. The overlap region was set to about 3 gap widths.

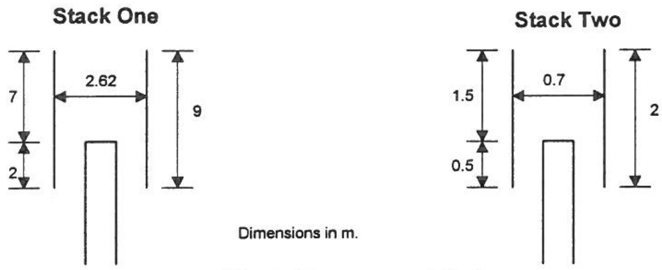

Fig. 2 The proposed design

## *RESULTS*

Outer stacks were manufactured to the dimensions given above and then the emissions concentrations were measured again. The results obtained are given in the following table.

| **flow parameters** | **Stack 1** | **Stack 2** |
|---|---|---|
| Stack diameter at sampling plane, m | 2.6 | 0.7 |
| average velocity, m/s | 5.2 | 6.3 |
| average temperature, deg C | 52 | 38 |
| flow rate at discharge conditions, $m^3$ / min | 1,700 | 150 |
| flow rate at dry NTP conditions, $m^3$ / min | 1,300 | 120 |
| **particulate matter** | | |
| concentration, mg / $m^3$ , at NTP | 330 | 280 |
| mass rate g / min | 430 | 34 |

The initial report back from the client was that the idea of adding the outer stack did not work. This was because the emissions concentrations were still above the required value of 250 mg/$m^3$. However, a closer look at the second set of measured results shows that in fact the idea had in fact worked quite well.

For stack 1 the flow rate at NTP conditions increased from 728 to 1300, a factor of 1.8. However, the mass flow rate of particulates increased from 320 to 430. If the particulate mass flow rate had remained the same, the concentration would have reduced to 430/1.8 = 239 mg/$m^3$ and so would have just met the specification of 250. In this case the increase in gas mass flow rate at NTP at about 1.8 was less than the design value of 2. The measured velocity profile was quite non-uniform indicating that enhanced mixing of the flows would be helpful.

For stack 2 the flow rate increased from 85 to 120, a factor of 1.41. If the emissions mass flow rate had remained at 23, the concentration of particulates would have reduced to 270 / 1.41 = 191 mg/$m^3$. For this stack the gas mass flow rate increased by 1.41, very close to the design value of 1.4.

## *CONCLUSIONS*

A relatively simple design procedure for sizing a secondary stack around an existing stack to reduce the concentrations of emissions has been developed. Measurements show that the prediction method works reasonably well.

## *REFERENCES*

1. White, FM, Viscous Fluid Flow, McGraw-Hill Book Company, 1974