Account the resistances under the action of the suction

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Abstract. In this paper we’ll show the interrelation between pressure suction and suction object. Suction force and air flow rate are determined as a function of the air pressure supplied to the suction. Here (unlike the earlier works) airflow losses are taken into account. In case the gaps between the suction surfaces are either too small or too large, suction force is replaced by repulsion. The math expressions that describe the interrelation between air flow rate and suction force will help us to choose optimal suction parameters.

I. Introduction

In technological machines, and printing machines in the first place, the aerodynamic paradox described by Clement and Desorme in 1826 (more commonly known as Venturi effect) is often used: in any given jet of air, some pressure drop is always found [1]. This phenomenon prevents the sheet from jumping over the front stops of sheet-fed printing machines [2] and stabilizes the sheet when ejected by the sheet dispenser [3]. It is also used in separators with “pressure” suctions [4, 5]: unlike vacuum suction, this type of suction allows detachable material to be shifted over the suction plane.

But in some cases, e.g. when blower bars are used, the air layer between the ribbon material and the bar is so reduced by ”suction” that the ink can get smudged.

II. Problem Statement

To makesuch devices more efficient, it is necessary to take into account not only the resulting ”suction” force, but also the thickness of the air layer. The latter depends on such parameters as feed air pressure and hole diameter.

Bystrova V.B. [6] conducted some theoretical studies of flows in the suction head. She showed that suction force F is proportional to the square of the ratio flow Q and gap h. In this expression, \( r \) – external suction radius (roof radius); \( r_{\text{out}} \) – hole radius; \( \rho \) – air density:

\[ F = \frac{\rho}{4\pi} \left( \frac{Q^2}{r_{\text{out}}^2} \right) \ln \frac{r}{r_{\text{out}}} \]

However, this expression does not take into account the ”knock-off” effect of the jet, and the consistency between the calculation and experimental results is lost. Beyer G. [7] conducted an experiment and connected this relation to the gap. However, for practical purposes, it is more important to know the relation of the force to the air pressure. The aim of the article is to clarify the interrelation between these parameters.
III. Theory
1. Calculation Model

To calculate air loss, let’s look at a suction model consisting of two discs both of radius $R_{\text{max}}$. The gap between them is $h$; one of the disks has a hole of radius $R_{\text{min}}$.

![Figure 1. Calculation model](image)

The current surface area of a cylinder of $R$ radius is $2\pi Rh$. Entrance area is $2\pi R_{\text{min}}h$, exit area $2\pi R_{\text{max}}h$.

The consumption is the same $= 2\pi R_{\text{max}}hV_a = 2\pi RhV_R$.

Hence the velocity for the current radius:

$V_R = \frac{R_{\text{max}}}{R} V_a$.

2. Air Resistance Losses

Pressure loss due to air resistance is estimated by Darcy formula [8]:

$$dp = \lambda \frac{dR}{R} \frac{V_R^2 \rho}{2}$$

The parameter and coefficient $\lambda$ both depend on speed.

In laminar flow the drag coefficient is [8]:

$$\lambda = \frac{64}{Re^\frac{1}{2}}$$

where $Re$ is Reynolds number: $Re = \frac{VD}{\nu}$; $\nu$ is the kinematic viscosity of the air.

For the slot, the hydraulic parameter $D = 2h$, by substituting these values, we get:

$$\lambda_R = \frac{64\nu}{2Vh} = \frac{64\nu\pi R}{Q}$$

Pressure loss in a thin cylindrical layer of thickness $dR$ and height $h$:

$$dp = \lambda_R \frac{dR}{2h} \frac{V_R^2 \rho}{2}$$

By replacing the velocity with the flow rate, we calculate the local pressure loss forgiven radius:

$$dp = \frac{64\nu\pi R^2}{Q} \left[ \frac{dR}{2h} \left( \frac{Q}{2\pi Rh} \right)^2 \frac{\rho}{2} \right]$$

or, to put it simple:
\[ dp = \frac{4\nu Q}{\pi R h^3} \cdot \rho \cdot dR. \] (1)

The pressure loss on the \( R_{\text{min}} \) to \( R_{\text{max}} \) section is an integral:

\[ \Delta p = \frac{4\nu Q}{\pi R^3} \rho \int_{R_{\text{min}}}^{R_{\text{max}}} \frac{1}{R^3} dR, \]

which results in:

\[ \Delta p = \frac{4\nu \cdot Q}{\pi \cdot R^3} \cdot \rho \cdot \ln \left( \frac{R_{\text{max}}}{R_{\text{min}}} \right). \]

Another reason for the energy loss of the airflow is the throttling in the entrance hole of diameter \( d_{\text{entr}} \) and the turning of the flow when leaving the bore in the gap. These local resistance losses are characterized by the following expression:

\[ \xi \frac{\rho}{2} V_{\text{hole}}^2, \]

where \( \xi \) is the local loss factor [7]. When the direction of flow is reversed by 90° \( \xi \approx 1 \).

Flow velocity in the hole:

\[ V_{\text{hole}} = \frac{4Q}{\pi d_{\text{hole}}^2}. \]

### 3. Flow Rate Determination

The energy balance by pressure \((p_1 - p_a)\) has three components:

- friction losses \( dp \);
- the energy of the outgoing jet \( V_{\text{Rmax}}^2 \frac{\rho}{2} \);
- jet swivel losses \( \xi \frac{\rho}{2} V_{\text{hole}}^2 \).

An equation reflecting this balance:

\[ p_1 - p_a = \Delta p + V_{\text{Rmax}}^2 \frac{\rho}{2} + \xi \frac{\rho}{2} V_{\text{hole}}^2. \]

By substituting the pressure loss here and expressing velocity by volume, we obtain:

\[ p_1 - p_a = \frac{4\nu \cdot Q}{\pi \cdot R^3} \cdot \rho \cdot \ln \left( \frac{R_{\text{max}}}{R_{\text{min}}} \right) + \frac{\rho}{2} \frac{Q^2}{(2\pi)^2 R^2 h^2} + \xi \frac{\rho}{2} V_{\text{hole}}^2. \]

With reference to volume, this expression is a quadratic equation, which gives the flow rate at a given pressure drop:

\[ Q = \frac{16\pi \cdot \nu \cdot R_{\text{max}}^2 \cdot \ln \left( \frac{R_{\text{max}}}{R_{\text{min}}} \right)}{h \cdot \left( 1 + \xi \frac{64\nu R_{\text{max}}^2 h^2}{d_{\text{hole}}^2} \right)} \left[ 1 + \frac{(p_1 - p_a)}{\rho \cdot V^2} \cdot \frac{h}{32 \cdot R_{\text{max}}^2 \left( \ln \left( \frac{R_{\text{max}}}{R_{\text{min}}} \right) \right)^2} \right]. \]

This relation is shown in Figure 2.
Figure 2. Flow rate in relation to the gap (with pressure $p_1=1.8$ atm, $p_a=1$ atm, $R_{max}=30$ mm, $R_{min}=10$ mm, $d_{hole}=5$ mm)

In the small gap region, using the approximation for small $\beta$:

$$\sqrt{1 + \beta - 1} \approx \beta,$$

we get:

$$Q = \frac{h}{4\pi R_{max}} \sqrt{\frac{64 R_{max}^2 h^2}{d_{hole}^4}} \sqrt{\frac{\left(p_1 - p_a\right)}{2\rho}}.$$

This expression proves that in a small gap region the flow rate is proportional to the gap (with other parameters constant), which does not contradict V. B. Bystrova’s formula.

4. Pressure in the Layer

To determine the suction force, it is necessary to estimate the pressure at the current radius, which is a variable value.

Knowing the flow rate, we can determine the relation of pressure loss and radius using expression (1) (the same as for $\Delta p$, but with varying radius). We use the same integration, but with varying upper integration limit:

$$dp(R) = \frac{4\nu Q}{\pi h^3} \int_{R_{min}}^{R} \frac{1}{R} dR = \frac{4\nu Q}{\pi h^3} \rho \ln \left( \frac{R}{R_{min}} \right).$$

The current pressure, depending on the radius $R$, can be found as the difference between the initial pressure, the friction losses, and energy of the exiting jet:

$$p(R,h) = p_1 - dp(R) - \left( \frac{Q(h)}{2\pi R h} \right)^2 \rho.$$

The pressure in the gap calculated by this expression at a small radius is subatmospheric. By increasing the radius, we generate superatmospheric pressure (the atmospheric pressure is assumed to be $10^{5}$ Pa).

5. Suction Force

By integrating the force over the annulus, we determine the total suction force (taking into account the "knock-off" effect of the jet:

$$F = \left[\int_{R_{min}}^{R_{max}} \left[p_a - p(R,h)\right] 2 \cdot \pi \cdot R \cdot dR\right] - p_1 \cdot \mu \cdot \pi \cdot \frac{d_{hole}^2}{4}.$$
IV. Discussion of Results

Thus we've shown that when we take into account the resistance of the air flow, the suction force is replaced by repulsion when the gaps between the suction surfaces and the object are either too small or too large (which is not described by V. B. Bystrova's model). If there are no other forces applied to the object (gravity included), then zero force is applied to the gap as aftermath of suction. If the gap gets smaller, the force will turn into repulsion, while if the gap gets larger, the suction force will increase. So, there is an area, where the suction process is stable. But if the impact on the object is greater, than the maximum, the process becomes unstable, and the object is pushed away from the suction.

V. Conclusions

We calculate the interrelation between the suction force and the gap and air pressure in the suction, which makes it possible to estimate the layer thickness between the suction and the object. Calculations of air flow losses show, that the suction force is replaced by repulsion as soon, as the gap gets out of a certain range of values. This will help to calculate suction parameters for printing presses.

So, it would be reasonable to find the maximum suction force as well, as the interrelation between the steepness of the force and the gap value. This will determine the conditions under which the sucked-in object vibrates.

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