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RESEARCH ARTICLE

DRYING INTENSIFICATION OF WET ELEMENTS

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ABSTRACT

The paper deals with drying of painted or wet elements by waste hot air flow and summarizes results of flow numerical simulations used as support for better design and higher efficiency of the drying equipment. Several added practical examples complete the overview.

INTRODUCTION

The paper deals with drying of painted prismatic elements by waste hot air flow and summarizes results of flow numerical simulations used as support for better design and higher efficiency of the drying equipment.

Actual situation

The waste hot air is coming through piping in flat drying channel. Along the channel move dried elements placed on two skew transporting belts. The secondary air suction is directly from the volume of surrounding hall without any treatment. Therefore, the uncontrolled changes of air parameters in surroundings influences the result of drying. Here takes place the first phase of drying, only, when solvents vaporize from the layer just applied varnish [2]. In the next equipment follows the second phase, hardening of varnish layer by UV light at higher temperature – this treatment is not the matter of this paper. The waste air from the second phase uses the first phase for drying. The aim is to increase the drying intensity, to dry the material reliably, so that they will not stick mutually; actually, the drying is not perfect sometimes. With higher drying intensity, it could be possible to shorten the drying channel, too. The method of flow numerical simulation is used for support of solution procedures and for preliminary verification of designed changes on the flow field in drying channel.

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Proposed steps of the solution

The first solved case (Par. 2) models the actual situation, for comparison with following new modifications. Some of them are standard designing procedures as another layout, dimensioning etc., the other need the use of flow numerical simulation.

- Air inlet in drying channel to relocate at the other end of drying channel, closer to the fan. Currently the air is conducted along the entire drying channel at its distant end and then through the entire channel back again, in the same direction as the dried material. Reversing the airflow the piping length will be substantially shorter, i.e. both flow resistance and heat losses are lower. Simultaneously the relative air velocity towards dried parts will be higher in the counter flow and it is possible to expect the increasing of both heat and mass transfer.
- Currently, the system of waste air uses only one fan. Using both installed fans, the velocity inside the drying channel will be double theoretically and the drying intensity increases, too. It will be necessary to double the cross section of inlet piping, from 175 on 250 mm.
- Inside the drying channel to install cross partitions, alternatively from upper and lower side. Such cross flow theoretically could to increase the drying effect.
- It is necessary to check force effects of the inlet flow on light dried elements.
- Additionally, at the air inlet into drying channel is supposed the system of verified drying nozzles [1], instead installed simple directional board. The second such system could be installed, if necessary, as

recirculating system inside channel. Such impact flows can further to intensify the drying process and the drying channel could be shorter.

- The waste air from the second phase (varnish hardening), used for the first phase (drying), contains acidic ingredients. They must be removed; therefore, the heat recuperation should be used for drying hot air.

Those preliminary simulations suppose a “hard” source of air, i.e. its flow is constant, regardless the actual flow resistance. The simulation of real operation in the drying channel needs the real flow characteristic of used fan (dependence of pressure on volume flow) – with some inserted partitions inside the flow resistance and the airflow, too, is changing in a non-linear manner and an iterative calculation must determine the real operational state. However, it will be checked in the last checking phase of definitive proposal.

Preliminary calculations

Simulation of the actual state

Prepared model is described as follows:

Geometry: Inlet piping of diameter 175 mm, length of 15 m, drying channel of 0.2x0.4 m, length of 12 m parallel with inlet, distance of both parallel channels of 2.5 m. Directional board is installed at the inlet in drying channel across the entire width, covering the inlet diameter and inclined of 15° below. Used longitudinal symmetry plane, therefore one symmetrical half is modelled and evaluated, only.

Mesh: Quick preliminary calculations use the rough mesh, the element size of 20 mm crosswise and 100 mm lengthwise. Nevertheless, in such rough mesh slow boundary layers on walls are well visible.

Boundary and initial conditions: From the inlet hot air (70°C), volume of 600 m^3/h the velocity is calculated as 2 m/s. To that, the necessary pressure gradient of 70 Pa was calculated in two iterative steps. Suction/exhaust from/in surroundings 0 Pa, isothermal model. Flow direction (2 m/s) identical with movement direction of transporting belt (0.2 m/s).

Solver: Stationary solution of longitudinally symmetrical half, ideal gas, turbulence model k-ε. Such general model description is identical for all solved cases. The isolines display results of main parameters of the flow field.

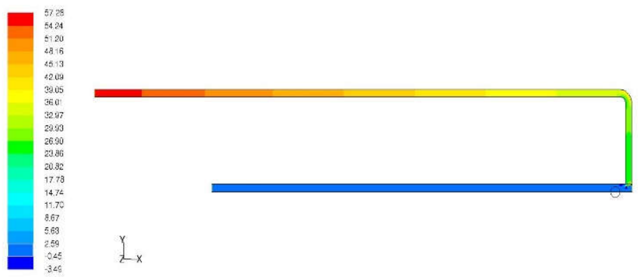

Fig. 1. Pressure field in inlet pipe (→) and in drying channel (←)

The pressure in the Fig. 1 is decreasing along the length, proportionally to the increasing flow resistance. Shortening the inlet directly from the left side the inlet length will be shorter, flow resistance is smaller and the airflow higher.

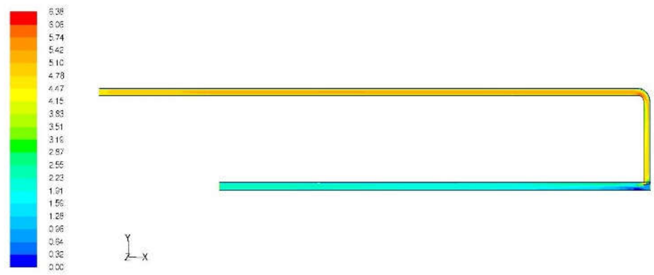

Fig. 2. Velocity field in the same system

After the Fig. 2, the higher value is in smaller cross section (= inlet).

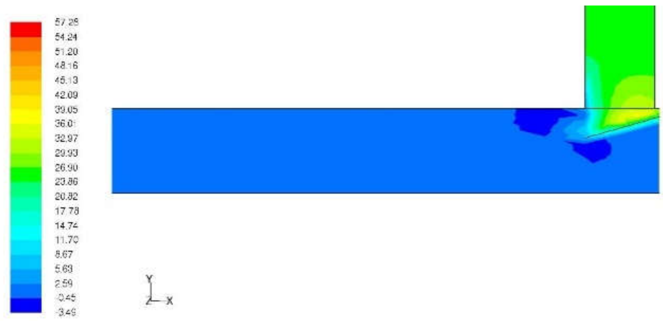

Fig. 3. Detail of pressure field inside of drying channel

The inlet partition in the Fig. 3 directs the inlet flow from vertical direction into horizontal one.

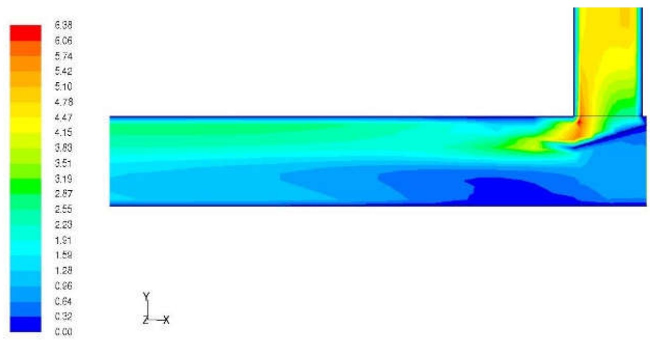

Fig. 4. Detail of velocity field directed by inlet partition

Fig. 4 presents the local maximum of velocity at the inlet into drying channel, where the sudden pressure drop is visible in the previous Fig. 3. In the lower part of the drying channel, there is visible intensive cold air suction from the surrounding (right).The next Fig. 5 shows the cross section at the end of inlet partition (right), where the flow field is very disturbed, due to the direction change of the inlet flow from vertical in horizontal and due to the intensive mixing with air from surrounding. Disturbances equalize during flow inside long drying channel, see the outlet (left).If the proposed impact nozzles are installed at the beginning of the drying channel and directed perpendicularly to the belt movement with dried elements [1], the backflow of hot air is expected – it is unsuitable from the energetic point of view. Solution that is more suitable would be the installation somewhere in the inner part of drying channel, where the flow is uniform and horizontal.

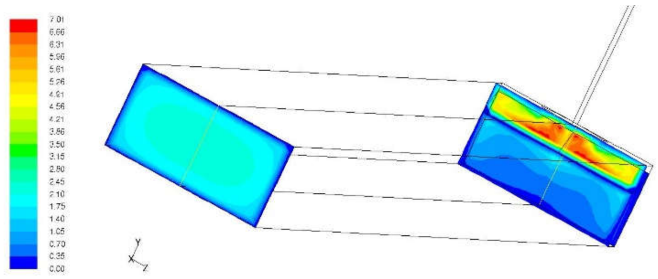

Fig. 5. Velocity field in cross sections

Inlet replacing

Long inlet pipe along the entire drying channel (see the Fig. 1 etc.) to the right side is not logical and should be substituted by shorter inlet just from the left side, near to the air source. Images of the flow field are similar, therefore not presented again. In the shorter pipe, the flow resistance is lower, for the same pressure gradient of 70 Pa the velocity is higher of about 15%. Without next modifications,there is expected higher drying output or for the same air velocity, the necessary pressure gradient is of 50 Pa, only.The flow direction (2 m/s) as counter flow to the belt direction (0.2 m/s), increases the relative velocity in the ratio of (2+0.2)/(2-0.2), i.e. of 22%, on contrary to the original case, where flow and belt move in the same direction. Proportionally increase both heat and mass transfer – drying. Graphs on the Fig. 6 a-b-c-d show profiles of temperature or humidity (y-axis) for drying air and dried material for both arrangements of movement directions – co-flow (actual) and counter flow (proposed) along the length of drying channel (x-axis).

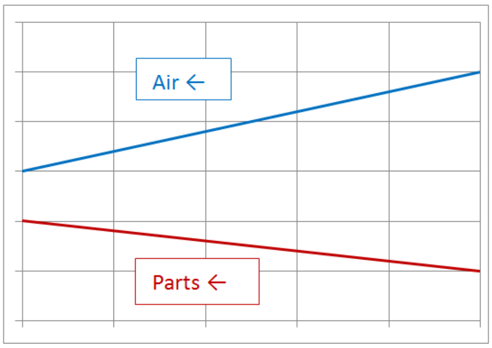

Fig. 6a. Temperature – co-flow

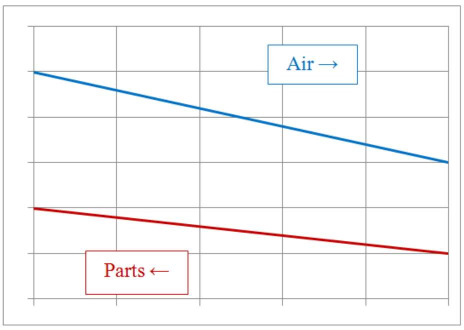

Fig. 6b. Temperature – counter flow

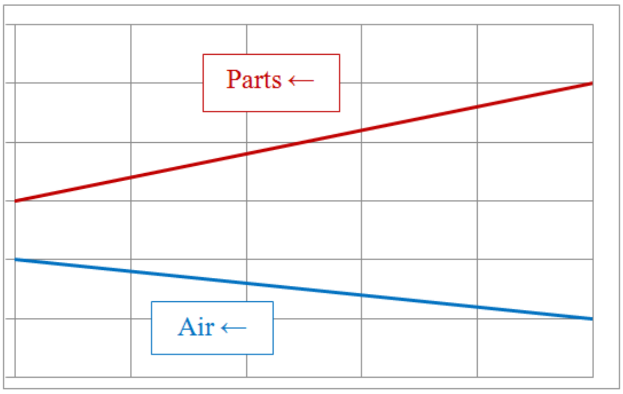

Fig. 6c. Humidity – co-flow

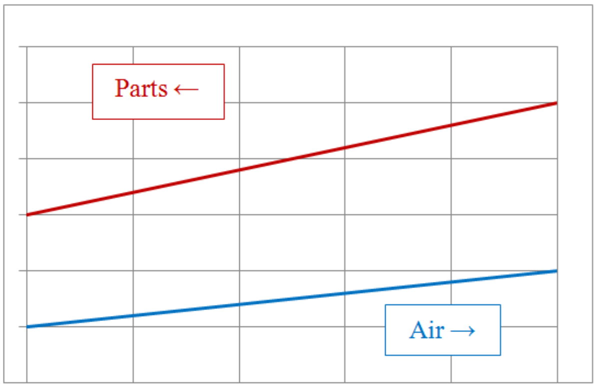

Fig. 6d. Humidity – counter flow

If both materials move as co-flow, in the same direction, temperatures and humidities of both materials are very distant at the beginning and very close at the end of drying channel - possible varnish cracking can arise. If both materials move as the counter flow, in opposite directions, the differences of parameters are not so extreme.

Double volume of air flow

Using both installed fans in common inlet piping, the double air volume (approx.) is coming in the drying channel. Contrary to the Par. II B, the cross section is larger of 250 mm, to preserve the same flow resistance (approx.). The drying channel remains the same; therefore, the air velocity around dried parts is double (approx.). The simulation uses the same pressure gradient of 70 Pa for comparison with previous solved cases. The character of the flow field images is similar, therefore not presented here.

Influence of internal partitions

Solution of drying channel alone, with added cross partitions of 50 mm in height, pitch of 0.5 m, alternately up and down. Larger partitions are not possible, because in the middle is situated the transporting belt. The same pressure gradient of 70 Pa as above.

In empty channel (Fig. 7) without arranged inlet is the high velocity of 8.2 m/s. With inserted partitions, it decreases at 2.7 m/s, only (Fig. 8), as the symptom of higher flow resistance. The effect of partitions is not important – not install.

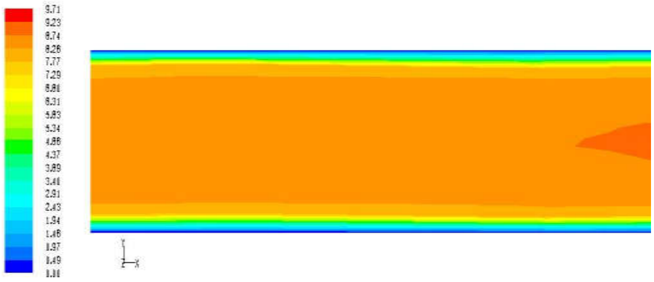

Fig. 7. Velocity field in smooth channel (average inlet velocity of 8.2 m/s)

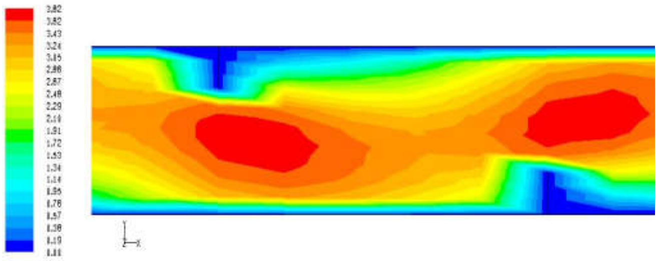

Fig. 8. Velocity field in channel with partitions (average inlet velocity of 2.7 m/s)

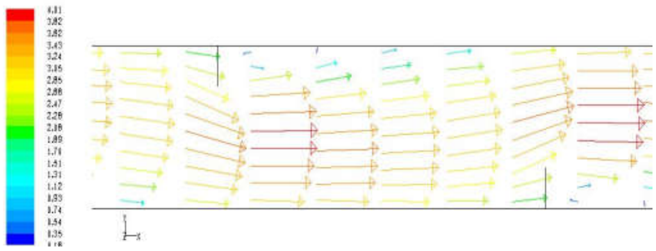

Fig. 9. Directional field – another image of the flow field with partitions

Force effect of inlet flow on dried elements

In the actual empty channel above are added dried parts of 240x16x3 mm, situated at the middle height of channel. Pitch of parts is 100 mm - not all parts are here, their real number is 2-3times higher. Presented results observe the inlet part (2 m) of the long channel, only. Contrary to previous models, the air temperatures are different here, of 330 K (57°C) – drying and of 290 K (27°C) - surroundings.By narrowing of skew inlet in the channel the local maximum of force effect on dried parts at the end of directional board is decreasing, the possibility of blowing out of hot drying air is suppressed and the force effect on dried parts is decreased, too. However, in the same time, the total flow resistance is increasing. For check the "empty" model without dried parts is solved, too, as checking case, the images of the flow field are similar, therefore not presented here.

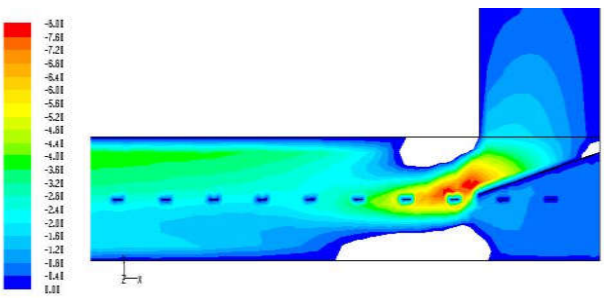

Fig. 10. Isolines of horizontal component of velocity

In this image with suppressed scale are removed two areas of backflow (two local vortexes in the separation zone at the inlet edge and in the area of mixing, the medium velocity of about 3.5 m/s.

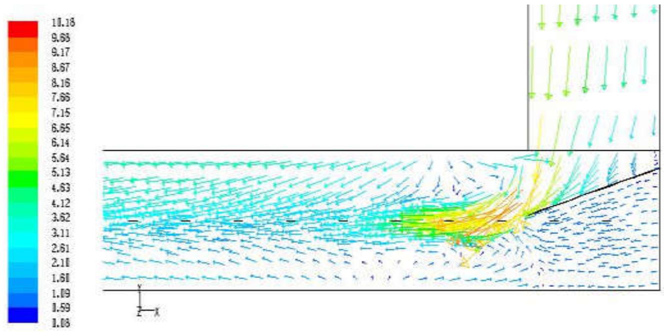

Fig. 11. Directional field

Another view on the inlet area of drying channel.

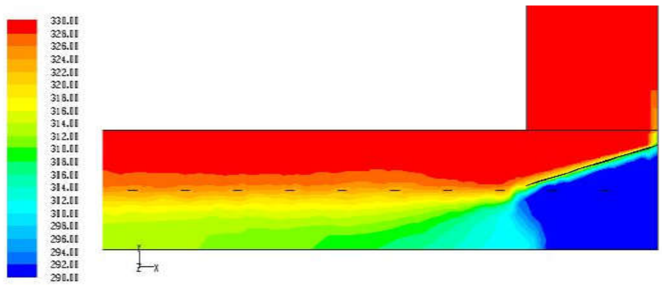

Fig. 12. Temperature field

In this model is visible the mixing of the hot drying air (from up) with cold air (from right), from surrounding. This cold air decreases the temperature of mixture and the drying efficiency, too. It should be better to add here some volume of warmer waste air.

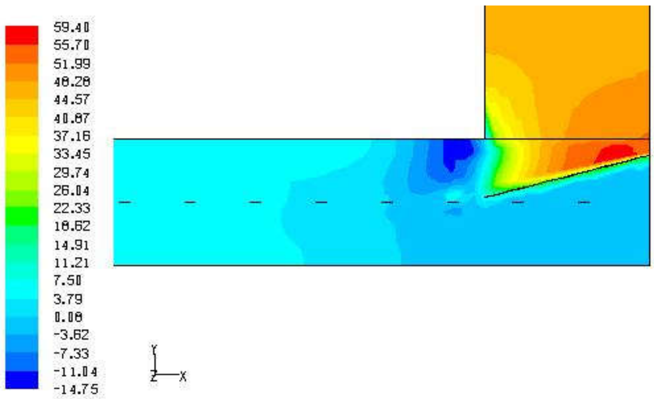

Fig. 13. Pressure field

Quick pressure decreasing in the relative narrow cross section between inlet pipe and drying channel – the pressure changes into velocity, see also the Fig. 3.

The force effects of the airflow are evaluated as vertical force Fy on the upper face of individual dried elements from the Fig. 10 etc. After the Fig. 14, it is locally different. All is valid for symmetrical half of each element; negative values mean the direction down (+y is up).

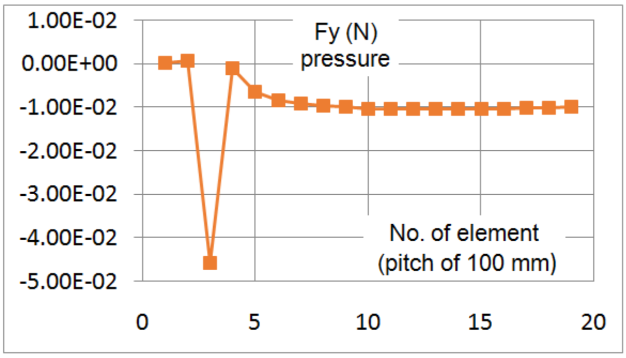

Fig. 14. Vertical force Fy (pressure) on dried elements

The vertical pressure force Fy is of two orders higher than the horizontal force Fx1 below, character of both components is similar. The same strong local extreme is at the end of directional partition. After the used system of coordinates, the values are negative = down, except small positive value in the position "2". The area of this position could be observed in detail later.

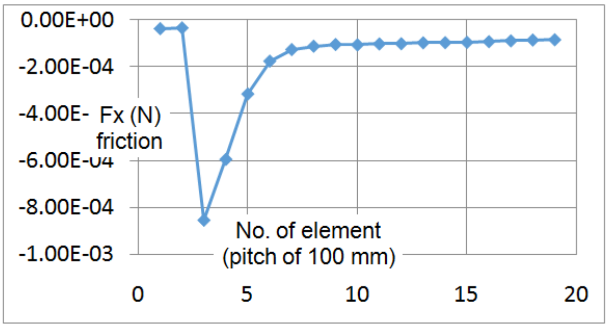

Fig. 15. Horizontal force Fx1 (shear) on dried elements

The horizontal force Fx1 is result of viscous friction of the flow on dried surface. The character is similar to vertical force Fy, but values are negligible, of two orders lower. From both graphs, it is visible that in the area of directional partition is possible to expect some problems during the operation, because the aerodynamic forces are here many times higher than further along the drying channel. The horizontal component could shift the dried element, placed on transporting belt.

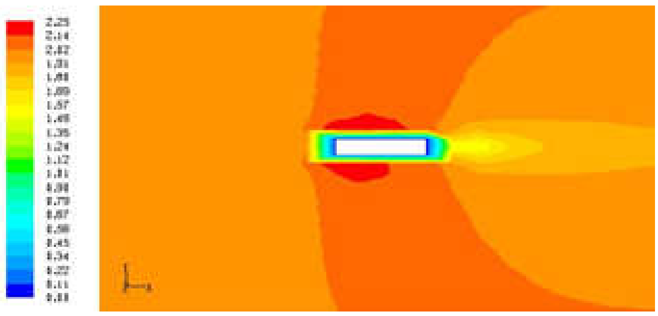

Fig. 16. Velocity field around blown element

The vertical component in this area is positive (up), theoretically could lift up the dried element. The previous case does not consider the thickness of elements of 3 mm, where on the front face arises next pressure force Fx2 in the direction of (-x). Simple model solves aerodynamic forces on one such element in steady airflow of 2 m/s. The Fig. 16 presents the detailed velocity field and the Fig. 17 the pressure field around one dried element – for the first orientation used rough mesh. Resulting forces in mN on individual faces summarizes the Table 1. Values are for symmetrical half of the element length. Typical maximum at sides, typical maximum at front face (stagnation point) and behind the body.

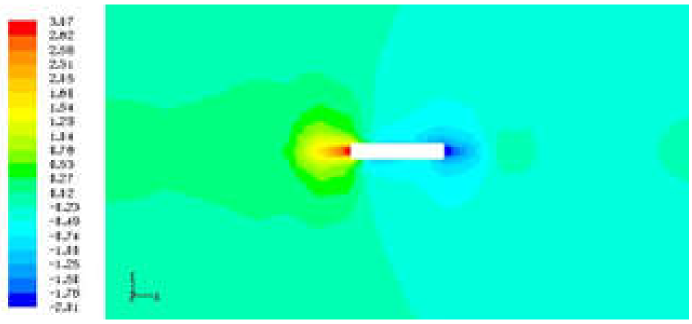

Fig. 17. Pressure field around blown element

High value at the stagnation point, negative value on backside.

Table 1. Aerodynamic forces [mN] on one-half element

Wall	Fx	Fy
lower	0.150	-1.583
upper	0.150	1.574
front	1.473	0
back	-0.821	0
sum	0.952	-0.009

The main item is the horizontal force Fx2 on the front face, which adds with the force on the backside (where the value is negative). Its absolute value is comparable with vertical force Fy, but on upper and lower face of element, the resulting force Fx is practically zero. The difference is in the graph Fig. 14. Next item is friction force Fx1 on upper and lower side of element, see the Fig. 15, but its value is practically 10 times lower than Fy. Next items on vertical sides are neglectable.

Summary of preliminary results

The Table 2 summarizes velocities in important cross sections of individual solved cases (Par. 2) and their relation to the original case. In general, each modification increases the air velocity inside, therefore increases both heat ad mass transfer, too.

Table 2. Velocities in cross sections of solved cases

		original	shorter inlet		Js250	
No.	position	m/s	m/s	%	m/s	%
1	Entry in the inlet 175 mm	4.67	5.41	116	4.59	98
2	End of directional partition	2.03	2.37	117	4.26	210
3	Suction at belt inlet	0.62	0.74	119	0.73	118
4	Exhaust at the belt outlet	1.95	2.27	116	3.44	176

Note for Js 250: The higher velocity value at the end of directional partition (No. 2) contrary to the value in outlet (No. 4) can be explained on the Fig. 4 etc. In the position No. 2 two streams of very different velocities are connected – quick flow from the fan and slow flow from surrounding. Therefore, the determination of medium velocity is not exact. On the contrary, at the outlet the flow field is not disturbed, so the determination of medium value is reliable. Shorter inlet means lower flow resistance and so the velocity increasing in the drying channel of about 20%. Proportionally the drying intensity increases, too. Use of both installed fans means next double approx. increasing of flow velocity, therefore next increasing of drying intensity. Generally, it is necessary to check, if too high dynamic effect of high velocity does not move by light dried elements. Entry cross section in drying channel cannot be fully shut, because here passes the transporting belt with material for drying. It is suitable this cross section to throttle as possible, to decrease the suction of cold air from surroundings – it is unsuitable from energetic point of view. It is possible that actually changed parameters of outside air can cause the situation, when the drying will not be sufficient. It could be better to bring some volume of hot waste air into this area, to be sure that air parameters are known and controlled and not random like weather. Preliminary simple relocation of hot air inlet on the nearer side removes problems of imperfect drying and that use of both installed fans brings so distinct increasing of drying effect, that it will be possible to shorten actual length of drying channel.

The change of air velocity direction towards dried material (opposite instead together) brings next velocity increasing around dried surfaces of about 22%. It is more suitable for the course of drying – at the beginning; the wet material is in contact with dry air, at the outlet the dried material with wet air. Temperature differences are not so extreme, so possible danger of cracking of dried surface is not so high. The inserted directional board suitably deflects the vertical stream of inlet air in the horizontal direction of dried material, with next suction of surroundings air by the ejection effect. If used here the system of impact nozzles with vertical streams [1], probably a part of this air will just flow out without any drying effect. Effect of aerodynamic forces on dried elements is the highest at the end of directional board. In a steady flow the highest force is the horizontal component, the vertical one can be neglected. Presented conclusions can help with design of more powerful, reliable and economic drying equipment.

Drying chamber II

This case describes very similar problem of chamber for drying of just painted parts [3] – they are not dried uniformly. In both velocity and temperature fields, see the Fig. 18 and Fig. 19 is visible an expressive short-circuit od air flow in the central part up, which is flowing through the chamber without important drying effect.

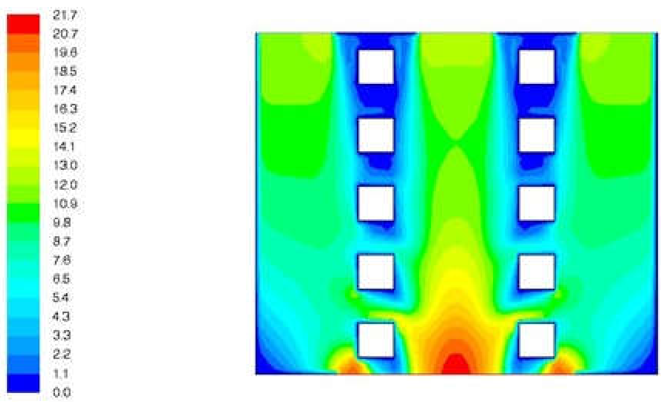

Fig. 18. Velocity field – actual state

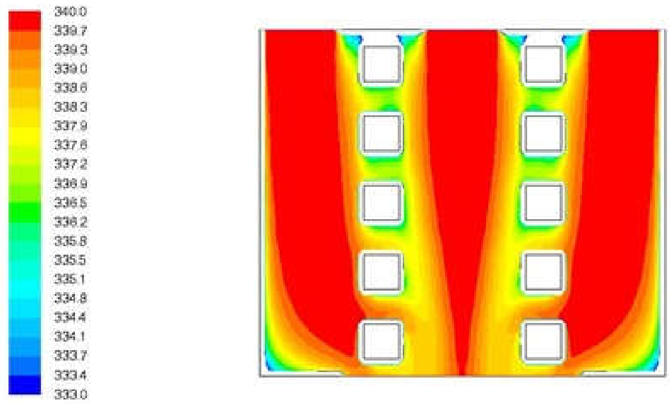

Fig. 19. Temperature field – actual state

Inserting some cross oriented partition, the parts are better blown and the drying effect is higher, see the Fig. 20 and Fig. 21.

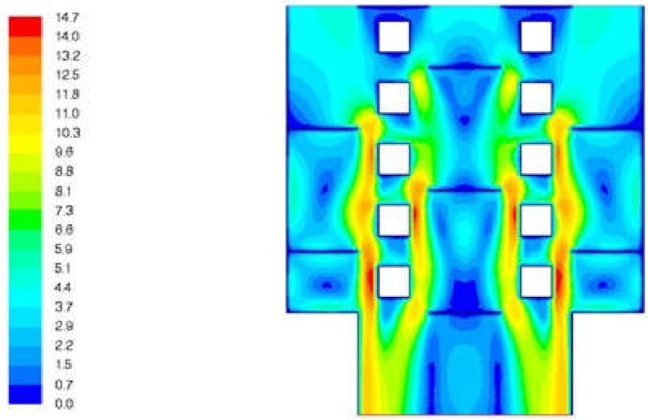

Fig. 20. Velocity field with partitions

Fig. 21. Temperature field with partitions (suppressed scale)

The influence of pressurized or exhausted chamber on the temperature field inside show next Figures as lengthwise cross sections of the chamber. The Fig. 22 presents the temperature field of pressurized chamber – the air of higher pressure is coming from up, exhaust is down into zero (atmosphere). In such chamber, a part of hot air with vapors of solvents is going out through the open sides. The Fig. 23 presents the temperature field of exhausted chamber – atmospheric pressure from up, under pressure down. In such chamber, some cold air from surroundings is coming in from open sides. Therefore, in the lower part the temperature is lower, so the drying of parts here is not intensive. The cold outer air influences minimum of 1 m inside in the chamber.

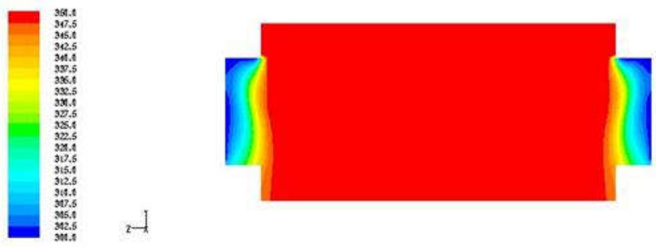

Fig. 22. Temperature field – pressure up, zero down

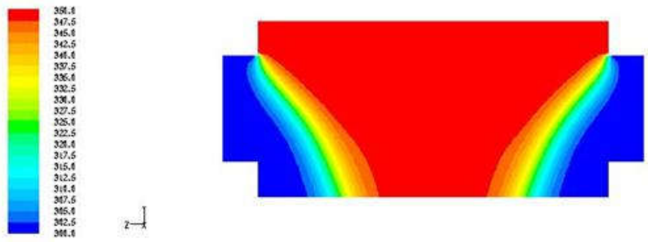

Fig. 23. Temperature field – zero up, exhaust down

Next cases of blown surfaces

In many industrial devices and equipment, the wet surfaces are blown by air from various reason – to heat or cold, to sweep, to dry etc. Several cases are presented in this supplement. Simple numerical simulation shows the reason of unsuitable operation and in the same time shows how to remedy it.

Drying intensification

The scheme of drying machine [4] is evident from the Fig. 18. The wide band of just printed plastic foil moves together with rotating cylinder of large diameter (down). The print is dried by the air from long and narrow cross-oriented nozzle. The machine output (= band velocity) increasing is not possible, because the print is not dried sufficiently.

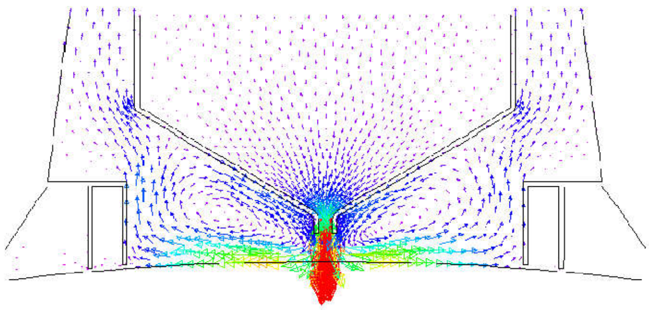

Fig. 18. Directional field – former arrangement

On the original arrangement there is visible that the incoming drying impact flow from up to down creates large areas of backflows, saturated by vapors of solvents. Therefore, an intense drying by such saturated flow along dried surface is not possible.

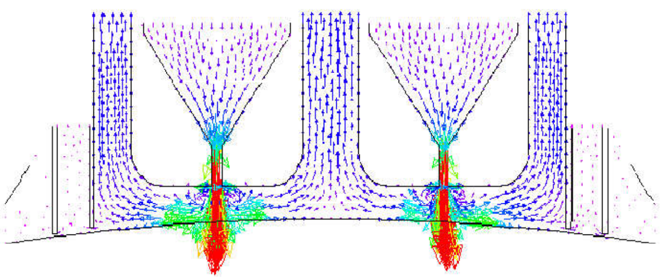

Fig. 19. Directional field – new arrangement

Simple shape modification assumes airflow along dried surface without backflows saturated by solvents vapors, it means that the vapors exhaust is better and so the heat and mass transfer are higher. Additionally, dividing the cross section of nozzle into two narrower pieces, the noise level is decreasing, too.

Sweeping of wet surface I

Manufactured parts are washed before painting and must be dried before that, see the scheme in the Fig. 20 [5]. Several air tubes are used for blowing air of low dynamic pressure, but the effect is not good. The dynamic effect of the airflow is feeble; the inner side of treated parts is not blown at all. Really, it is not a drying device, but a sweeping one, to sweep in this phase the large water drops sticked on the surface and in the next phase to dry the remaining thin water film on surfaces.

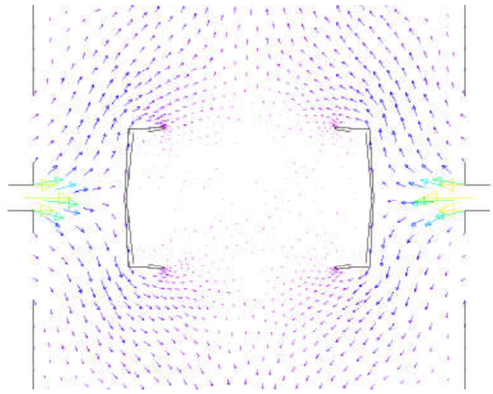

Fig. 20. Directional field – former unsuitable arrangement

Suitable configuration after the Fig. 21 uses small air guns operated by robot, which can blow all inner surfaces and details, as necessary. Numerical flow simulation shows all details of the directional or velocity field for any position of blowing gun, as check of a suitable operation [3].

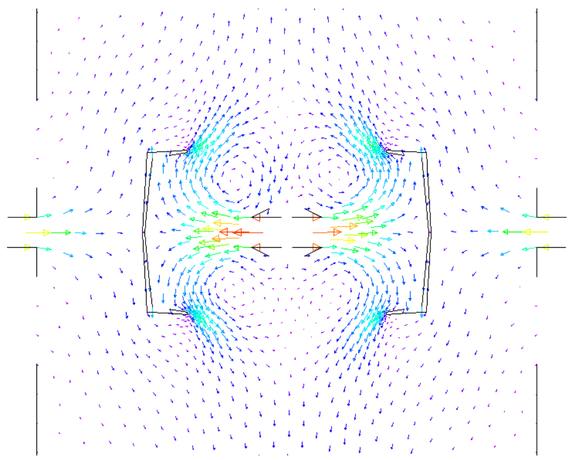

Fig. 21. Directional field – new arrangement

Sweeping of wet surface II

In this similar case the wet surface of the large glass table, moving according to the arrow, is cleaned by air flows from large cross nozzles, situated up and down, see the Fig. 22.

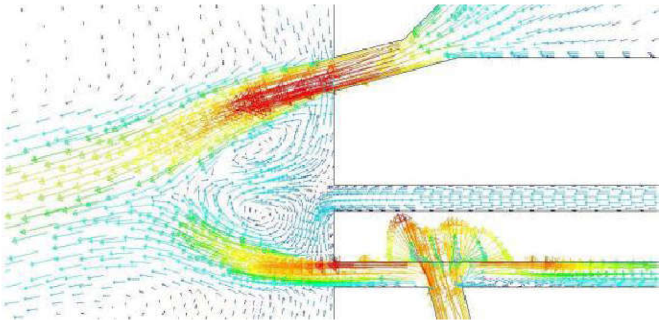

Fig. 22. Directional field – the treated table in any middle position

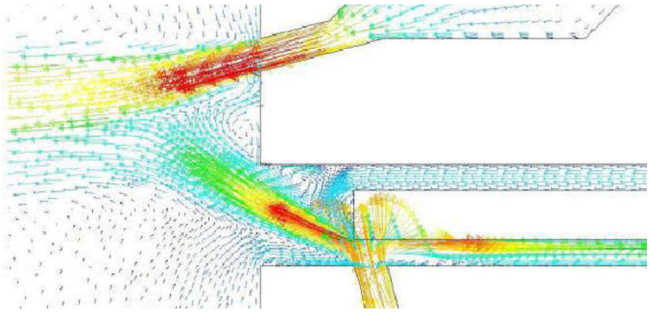

Fig. 23. Directional field – the treated table in ending position

However, at the end of glass table some part of the lower airflow is coming back and the cleaned surface is contaminated again, see the Fig. 23. It is visible that the nozzle direction is not good and after its modification, the situation is better.

Clean rooms

Before the entry of personal in the clean room, all must be cleaned by so-called air shower. Used airflows must be sufficiently intensive, but without unpleasant influence on persons. This numerical simulation easily shows the velocity field of air nozzles at designed positions (for instance the diagonal vertical cross section in the Fig. 24), the dynamic effect on the surface of human body (see the Fig. 25), the velocity field in important horizontal cross-sections (head and foots levels, in the Fig. 26) etc. Therefore, it is possible to evaluate in advance all effects of designed layout.

Fig. 24. Velocity field in air shower

Fig. 25. Dynamic effect of the air shower on body surface

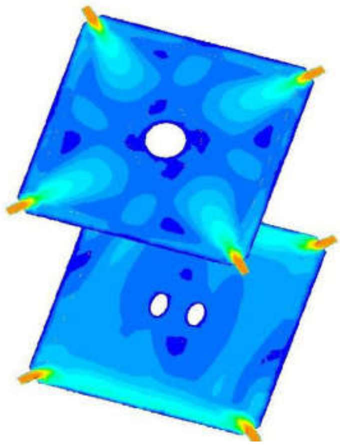

Fig. 26. Velocity field at levels of head and foots

Conclusion

The paper describes the simulated operation of various industrial equipments for drying or sweeping of wet surfaces, not published till today. In general, they are used standard principles of fluid mechanics and thermo mechanics, well known for technicians and engineers, therefore without next references. Used method of flow numerical simulations allows the enlargement on complicated 3D reality and shows the reason of insufficient output and efficiency of various observed equipments. Simultaneously the method is used for prediction of suitable procedures, how to increase the effectivity and output of observed equipments.

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