Contemporary Engineering Sciences, Vol. 7, 2014, no. 33, 1793 - 1806
HIKARI Ltd, www.m-hikari.com
http://dx.doi.org/10.12988/ces.2014.410190

Line Summary of Approaches for Improving Vibrational Reliability of Thermomechanical Equipment and Its Interconnecting Pipelines at Thermal Power Plant

Arkadiy Zaryankin

National Research University “Moscow Power Engineering Institute”
Krasnokazarmennaya Street 14, Moscow, Russian Federation

Nikolay Rogalev

National Research University “Moscow Power Engineering Institute”
Krasnokazarmennaya Street 14, Moscow, Russian Federation

Andrey Rogalev

National Research University “Moscow Power Engineering Institute”
Krasnokazarmennaya Street 14, Moscow, Russian Federation

Anna Kocherova

National Research University “Moscow Power Engineering Institute”
Krasnokazarmennaya Street 14, Moscow, Russian Federation

Wadim Strielkowski

Charles University in Prague, Faculty of Social Sciences,
Smetanovo nábř. 6, 110 01, Praha 1, Prague, Czech Republic

Abstract

A central problem in engineering of power-generating equipment, beside the quest for economy, is the problem of ensuring reliability of equipment and branched pipeline systems for circulation of process media. When analyzing causes of component failures in thermomechanical installations, flow control devices and pipelines, it should be noted that such failures most often result from dynamic loads on walls of these objects exposed to flowing media. Such loads are an immediate result of turbulent flow of the process medium. This turbulence is characterized by extremely non-uniform flow field and pressure pulsations of significant amplitude occurring in a broad band of frequencies. For that reason, this paper will be mainly concerned with the development and experimental studies of new approaches to dampening flow perturbations introduced by flow control devices, turbine stages, flow direction changes at pipeline bends, control valves of steam turbines etc. Findings are presented as specific examples showing the potential for a sharp reduction of dynamic loads on walls of various devices exposed to flowing medium. These involve both specially designed aerodynamic filters and direct action to modify flow behavior of the process medium in areas adjacent to walls. It is shown that the application of proposed pulsation dampener designs has the potential of twofold to threefold improvement in vibrational reliability of equipment and its interconnecting pipelines.

Keywords: vibration, pressure pulsations, pipeline, vortex dampener, perforation, aerodynamic filter, vibration acceleration**,** vibration velocity

1 Introduction

The state of vibrations in installations and their interconnecting pipelines are determined by the magnitude of pressure pulsations caused by process medium flowing through. In turn, frequencies and amplitudes of these pressure pulsations in a traveling flow are immediately determined by the degree of aerodynamic perfection of flow-through passages of particular devices.

Unfortunately, designers of flow control devices pay little attention to fluid dynamics. As a result, these very devices, including parts of power-generating equipment, are responsible for generating pressure pulsations of extreme amplitudes. For example, full-scale tests of steam distribution systems for K-800-240 and K-200-130 turbines manufactured by LMZ (now known as OJSC Power Machines, Russia) [8, 11] the magnitude of pressure pulsations Δp downstream of control valves may be as high as 8…12% of original steam pressure p_0. In absolute terms it would be 2.0 to 2.5 MPa for a K-800-240 turbine and 1.1 to 1.4 MPa for a K-200-130 turbine.

A similar magnitude of pressure pulsations was measured downstream of a cage-type valve installed on a feed water line of Balakovo NPP [6]. The situation was just as serious when a K-1000-65 turbine made by Skoda was commissioned at Temelin NPP in Czech Republic [13], with severe pressure pulsations in steam lines supplying steam from outboard control valves to turbine stage 1.

In some instances the transition from stationary to non-stationary flow in geometrically complex ducts may be preceded by an extremely non-uniform flow fields at the outset. The impact of this factor on all of properties of a particular object was studied by multiple researchers in the past [4, 5, 7, 9, 12]. These works described the extent to which a non-uniform flow field brings about adverse changes in energy losses, flow, power and vibrational properties of diffusers, turbine stages, valves, exhaust manifolds and other objects.

However, all those works, with the exception of [7] did not consider the matter of counteracting the consequences of non-stationary turbulent flows arising in ducts by actively modifying these flows using various pressure pulsation dampeners (aerodynamic filters).

Vibrational reliability of thermomechanical equipment at thermal and nuclear power is generally achieved by avoiding natural frequencies of equipment components and the band of perturbing frequencies inherent in equipment operation [1, 10].

Still, in some cases there are no options for substantially improving vibrational stability of certain equipment items. In particular, it is virtually impossible to adjust natural frequencies of pipelines so that they would be isolated from dynamic disturbing forces produced by the action of flow on pipeline walls, as the frequency spectrum of these forces spans a range from several hertz to 5…10 kHz.

For this reason, passive vibration control techniques are mostly used for reducing vibrations of pipeline systems. These include changing pipeline configurations, adding more supports, and improving rigidity by choosing thicker-walled pipes.

Pipeline supports with hydraulic dampeners have demonstrated promising performance [2].

It can be seen quite easily that all mentioned techniques for improving vibrational reliability of pipelines and equipment address effects rather than the root cause of the problem.

Therefore, reports of successful dampening of pressure pulsations by means of actively modifying the behavior of process media flow in ducts and pipes are of much value [3, 14, 16, 17, 18, 19].

From the standpoint of theoretical fluid mechanics, the occurrence of intense pressure pulsations in flowing media is most often caused by: (a) detachment of flow from its enveloping surface; (b) transition from confusor to diffusor flow pattern; (c) a change in the direction of pipeline that carries process media.

Thus, in order to improve vibrational performance of equipment and associated piping, designers will have to ensure that flow remains attached to inner surfaces of passages as much as possible. This approach may not be physically feasible for some devices owing to their structural features (e.g. passages of gate valves or rotary dampers). This naturally calls for introducing devices that would either effectively quell pressure pulsations in a running flow or restrict their effect on duct walls where the flow of process media is highly non-stationary.

These approaches to countering adverse effects of pressure pulsations in a running flow will be illustrated below using specific examples.

2 Perturbations introduced by gate valves into pipelines

The gate valve shown in Fig. 1 is a classic example of a device where detached flow arises inevitably.

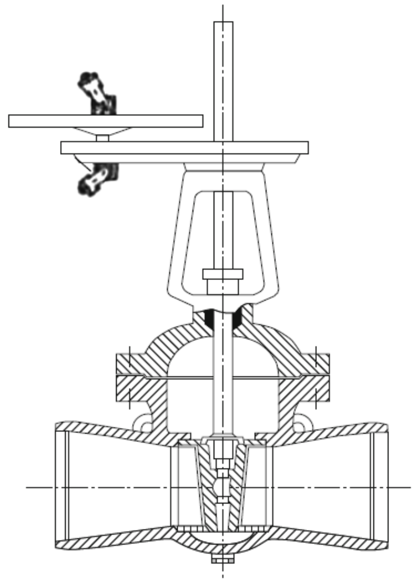

Fig. 1: Standard gate valve

Despite all configuration advantages provided by these devices, a partially open gate valve generates discrete mature vortices downstream that become enveloped in the main (carrying) flow as solid bodies and move significantly slower than does the main slow. The difference between these velocities (known as the slip factor) depends on intensity of generated vortical structures characterized by velocity circulation inside them. Assuming a constant flow rate of process medium, higher velocity circulation would increase the difference between individual velocities of vortex structures and the main flow velocity and therefore decrease the frequency of velocity and pressure arising within the flow as a result of interaction between discrete vortices and the running flow.

In essence, non-stationary flow of two-component medium arises downstream of gate valves. This development is characterized by an extremely wide spectrum of pulsations of velocities and amplitudes of all flow parameters. Dynamic loads originating in these pulsations are absorbed by walls of downstream pipelines and all parts of the gate valve itself.

Finding themselves most disadvantaged from dynamic reliability standpoint are block valves that open without touching their seats, restricting their application for flow control to simple shut-off functions. Another significant operational drawback of block valves is the need to apply large forces to move wedge-shaped gate discs off wedge-shaped seats. For that reason gate discs with parallel surfaces are commonly used to control process media flow. However, this solution fails to ensure sufficient obstruction of the valve passage.

While both types of valves introduce virtually identical perturbations into the flow, the design with parallel disc surfaces ensures that the disc remains pressed against the surface of the respective component in all positions.

Pressure pulsation amplitude and frequency in the flow downstream of gate valves determines the vibrational condition of all downstream pipeline. As an example, Fig. 2 shows an oscillogram of vibrational accelerations *A* in an inlet section of service water return pipeline equipped with a gate valve that is opened to 40% of its total lift [19].

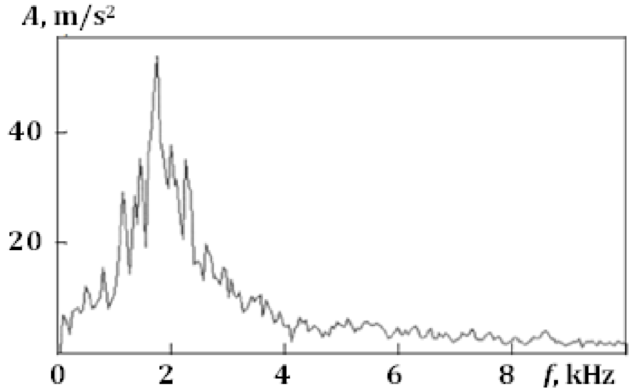

Fig. 2: Oscillogram of vibrational acceleration at inlet of system water return pipeline

Vibrational acceleration was the highest (53.5 m/s^2) at frequency f_c = 1750 Hz. At $f > f_c$ and $f < f_c$ vibrational accelerations have declined although they remained high enough both in low-frequency ($f < f_c$) and low-frequency ($f > f_c$) bands. Frequencies at which vibrational accelerations exceed 4 m/s^2 are observed between 2…5 Hz and 6 kHz, while vibrational motion of the pipeline section adjacent to connecting flange reaches 980…1150 μm.

3 Innovative shut-off/throttling gate valve

A highly practical design of a gate valve would combine advantages of gate valves and parallel-disc block valves in a single device while avoiding the above-mentioned shortcomings and creating as little flow perturbations upon entry into downstream pipeline as possible.

All three requirements are met to a substantial degree by a gate valve designed by ENTEK CJSC as shown in Fig. 3 [17, 19].

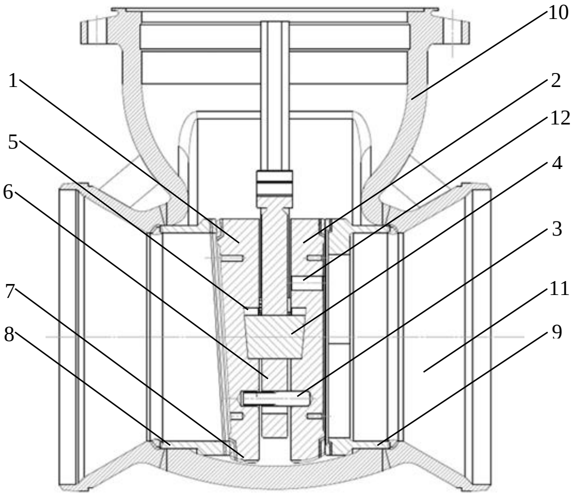

Fig. 3: Gate valve designed by ENTEK OJSC

In this valve the gate comprises a combination of shut-off disc *1* that has its working surface tilted at 3.5° against vertical axis and control disc *2* having its surface located at a right angle to the longitudinal axis of the gate valve. Three cylindrical axles *3* are fixed rigidly to its inner surface. Their splined ends match three holes on inner surface of the shut-off disc *1*. Thus, the shut-off disc is free to move in axial direction relative to the control disc. A two-sided symmetrical wedge *4* installed between gate discs enters into the respective grooves *5* on inner disc surfaces. The wedge *4* slides into holes in lift plate *6*.

To prevent washout erosion of shut-off and control disc edges exposed to fast-flowing process medium, anti-surge slits *7* (deep enough) are provided in the area of contact with the flow, ensuring simultaneous circumferential stabilization of flow. Both the shut-off disc seat *8* and control disc seat *9* are welded inside the gate valve body *10*.

The seat *9* is shaped to ensure linear flow control response as shown in Fig. 4a. The outlet part of the valve body has a slotted vortex suppressor *11* shown in Fig. 4b.

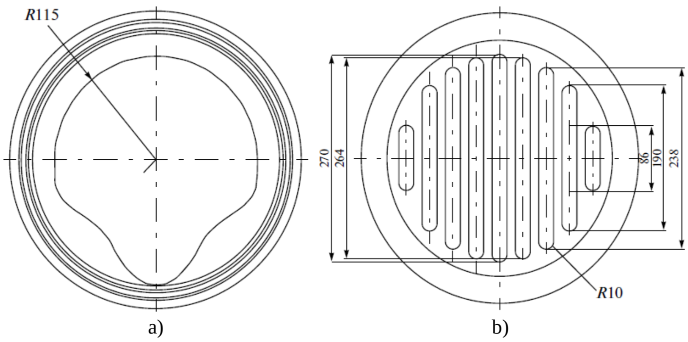

Fig. 4: Linear-response shape of gate valve seat (a) and slotted vortex suppressor (b) for Ø400 mm pipelines

When the plate is lifted *6* (see Fig. 3) the wedge *4* travels inside disc grooves *1* and *2* from the bottom to the top position, relieving the shut-off disc of axial thrust. The pressure of process medium then shifts this disc in axial direction along splined axes *3* to a distance equal the width of the gap between wedge surface and inner surface of its groove *5*, allowing the gate to lift freely as the lifting force is now only determined by the force of friction between seat *9* and control disc *2*. In order to decrease this force, the disc *2* is provided with three relief openings *12* reducing the force that presses the disc into seat *9*.

With these structural modifications, the gate valve can be considered as a combination of control and shut-off devices. In addition, dynamic stresses acting on walls of adjoining pipeline are reduced sharply thanks to flow stabilization techniques.

This is confirmed by an oscillogram of vibration accelerations plotted in Fig. 5. This diagram has been obtained in the same pipeline location as its counterpart in Fig. 2 plotted using a standard wedge-type gate valve. The oscillogram in Fig. 5 shows that, with the new gate valve installed, intense vibrational accelerations (60 m/s^2) remained only within a narrow band of resonance frequencies (f_c = 1100 Hz); at frequencies greater than 4000 Hz, vibrational accelerations were consistently less than 0.5 m/s^2.

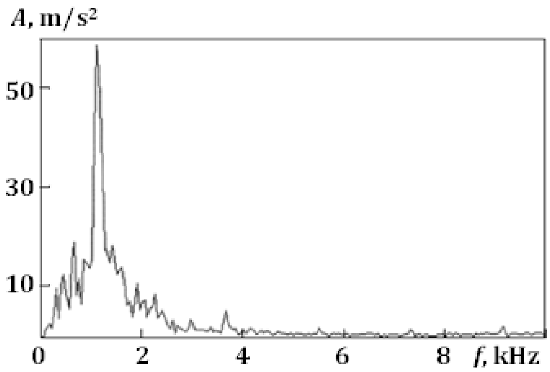

Fig. 5: Oscillogram of vibrational accelerations after installing the new gate valve

Vibrational movements declined at the same time to just 120 μm.

The foregoing method for reducing dynamic loads on pipeline walls was based on dampening pressure pulsations immediately within the passage of a flow control device.

Another, simpler and cheaper method for reducing dynamic loads involves dampening pressure pulsations in the pipeline itself or devising wall-side aerodynamic dampeners protecting pipeline walls from direct contact with pulsating flow.

4 Aerodynamic filters for reducing pressure pulsations in pipelines

As it indicated above, the amplitude and frequency of pressure pulsations in a flow are determined by the intensity of vortical structures (vortex kernels) that are similar to hard bodies inserted randomly into the main carrying flow pattern. Due to the discrepancy between motion velocities of these kernels $u_я$ and flow velocity u_i they become surrounded by the flow with a relative velocity (slip velocity) equal to $\Delta u_i = u_i - u_я$. Increasing intensity of vortex motion (velocity circulation) in these vortical structures leads to higher slip velocity u_i and, consequently, pulsations of pressure (as well as other flow variables) become more intense in amplitude and less frequent.

It is known that the greater part of pulsation energy is contributed by low-frequency pulsations of flow variables. As pulsations frequency increases (with vortex kernels becoming smaller), the energy of pulsational movement diminishes rapidly. At higher frequencies (f > 5 kHz) the pulsational motion extinguishes rather quickly.

In other words, increased dimensions of vortex kernels occurring inside flowing medium mean increased energy of pulsational motion and, therefore, higher dynamic loads on enveloping surfaces.

These considerations logically lead to an obvious method of reducing dynamic loads on walls of any ducts, including pipeline walls. This method involves breaking large vortex kernels into smaller structures. It was put into practice in a new gate valve design (see Fig. 3) having a slotted vortex suppressor at its outlet to withhold large vortex structures from entering the downstream pipeline.

Similar vortex suppressors (aerodynamic filters) can be installed in troublesome locations of any pipelines. It should be noted however than introduction of any device with a narrower passage into the pipe will inevitably result in increased hydraulic resistance with a consequent increase of power expended on transfer of process medium. Accordingly, aerodynamic filters must be designed as stand-alone devices with extra opening area immediately upstream of the filter.

Such an aerodynamic filter designed for dampening of pulsations in a high-pressure steam line transferring steam from control valves to a steam turbine is shown in Fig. 6. In this case, the a non-stationary media flow with a high amplitude of pressure pulsations runs into a slotted disc (the aerodynamic filter) that breaks large vortex kernels into smaller vortical structures nearly evenly distributed across the passage downstream of slotted disc. The diameter of this disc D_2 is computed assuming equality of total effective area of slots F_{slot}^{eff} to the flow section of pipeline with a diameter D_1.

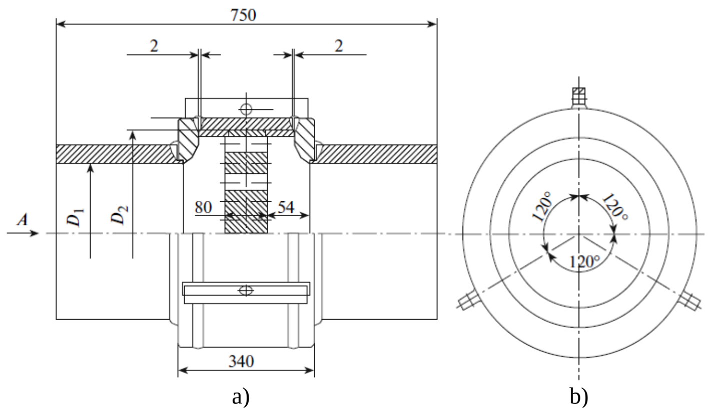

Fig. 6: Aerodynamic filter (vortex suppressor) for a high-pressure pipeline (D_1 = 285 mm, D_2 = 450 mm)

Effective area of slots is understood as a product of total geometric area of these slots of diameter *d* and flow factor μ i.e.

$$F_{пер}^{эф} = \mu \frac{\pi d^2}{4} n = \frac{\pi D_1^2}{4} \tag{1}$$

Whence, the number of slots *n* is

$$n = \frac{1}{\mu} \frac{D_1^2}{d^2} \tag{2}$$

Next, the pass-through ratio *k* is introduced as total geometrical area of slots divided by the area of the disc with diameter D_2. Then,

$$k = \frac{d^2}{D_2^2} = \frac{D_1^2}{\mu D_2^2} \tag{3}$$

Whence

$$D_2 = D_1 \sqrt{\frac{1}{k\mu}} \tag{4}$$

For cylindrical slots, the flow factor μ would depend on dimensionless thickness of the disc $\bar{b} = b\ /\ d$ and will vary between 0.70 and 0.85. Smaller values correspond to thicker discs ($\bar{b} > 10$).

The effect of aerodynamic dampener in question on the amplitude of pressure pulsations in the pipeline can be judged using oscillograms platted in Fig. 7 [3]. The amplitude of pressure pulsations downstream of aerodynamic filter has been reduced almost 3 times while vibrational movements measured on the pipeline downstream of the filter have declined by a factor of 2, 2 times.

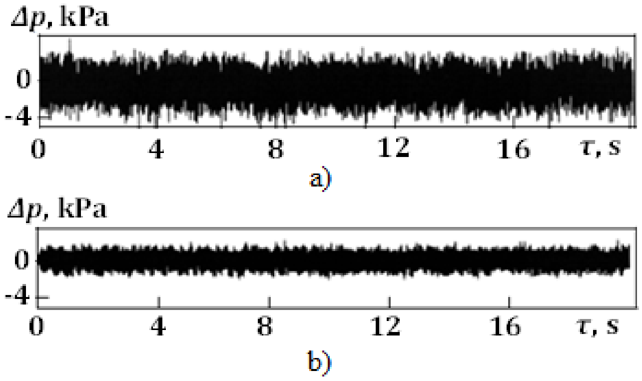

Fig. 7: Oscillograms of pressure pulsations upstream (*a*) and downstream (*б*) of the vortex suppressor.

5 Wall-side pressure pulsation dampeners

The method for dampening pressure pulsations immediately at walls using cylindrical slotted screens [18] is of much practical interest.

A drawing of a screened pipeline section is shown in Fig. 8.

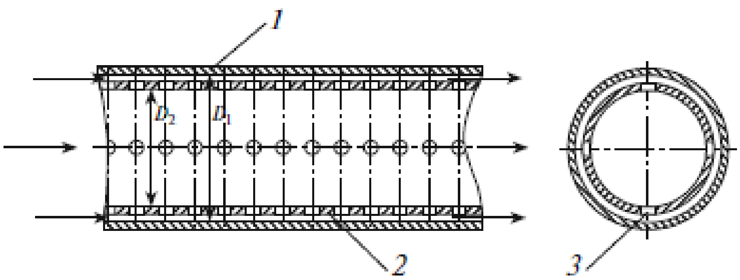

Fig. 8: Drawing of pipeline section under study

Inside the pipe *1* a slotted cylinder *2* is installed on longitudinal fins *3*. The cylinder has a diameter D_2 = (0.90…0.95) D_1 (D_1 is the pipeline diameter). Increased friction forces in the narrow annular gap between the inner surface of the pipe and the outer surface of the screen cause pressure pulsations to diminish. This "liquid" protective layer is an effective dampener for all the severe pulsations generated in the flow by upstream flow control devices.

The screen has been installed in the pipeline downstream of an angular control valve after the flow has passed through a 90° bend. At a distance of four times the diameter of the pipeline downstream of the bend and for a process medium flowing at 80 m/s, vibrational motion has declined almost three times compared to an unscreened pipeline.

6 Vortex motion dampening and reduction of pressure pulsations in exhaust manifolds of steam turbines

The problem of dampening large-scale vortical motion and equalizing flow fields in ducts of arbitrary shape can be addressed effectively by using "honeycomb" devices – assemblies of plates intersecting at a right angle to form a system of rectangular ducts. These devices would be practical for ducts with large and very large cross-section areas.

For turbine machinery in particular, a system for vortical motion dampening and flow field equalization was first designed in 1995 in the Moscow Power Engineering Institute in cooperation with ENTEK CJSC for exhaust manifolds of ABB Zamech 13K215 and ABB 18K360 steam turbines [15]. These devices were placed at the bottom of exhaust manifolds in locations where powerful concentrated vortices occurred (Fig. 9).

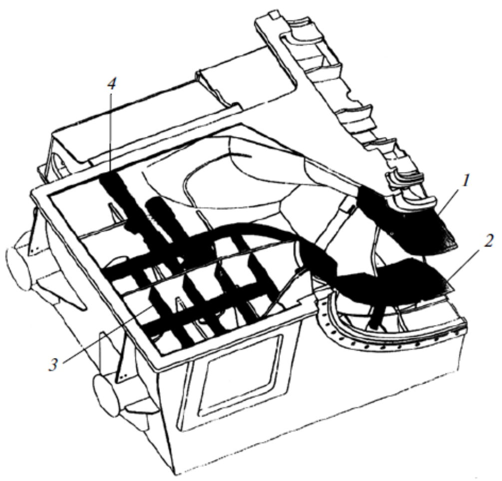

Fig. 9: Bottom part of LP cylinder in ABB Zamech 13K215 turbine
1– inner diffusor contour (bottom part); *2*– outer diffusor contour (top part); *3*– vortex suppression grid; *4*– stiffening tubes

Studies performed using exhaust manifold models and actual operating turbines [3] have shown that such vortex suppression grids can be successfully applied to reduce resistance in the steam supply system feeding the condenser by 10%, suppress vibrational motion measured at manifold housing by 30% to 35%, and eliminate backflow in the outlet of these manifolds almost completely [15].

7 Main conclusions

Our studies indicate that:

- Partially open gate valves result in sustained non-stationary movement downstream with pressure pulsations of severe magnitudes resulting in vibrational motion that may jeopardize reliability of downstream pipelines.

- Pressure pulsations within the flow can be brought down efficiently by installing slotted or perforated discs (aerodynamic filters), as well as mounting plate-type vortex suppressors immediately inside valve housings or inserting similar aerodynamic filters into pipelines; depending on initial magnitude of process pressure pulsations in the pipeline, these methods bring down pipeline vibrations by a factor of 2 to 10.
- Wall-side slotted screens are capable of reducing dynamic action of flow on pipeline walls by 2 to 3 times.

Acknowledgements. This study conducted by National Research University "Moscow Power Engineering Institute" has been sponsored financially by the Russian Federation through the Ministry of Education and Science of the Russian Federation under Subsidy Agreement # 14.574.21.0016 of June 17th 2014 as a part of the Federal Targeted Programme for R & D in Priority Fields for the Development of Russia's S & T Complex for 2014-2020. Applied Scientific Research Unique Identifier: RFMEFI57414X0016.

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Received: October 17, 2014; Published: December 3, 2014