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Stabilization of Flow Through Steam-Turbine Control Valves

After observing the abrupt variations in flow on an aerodynamic model having the form of a conventional valve, modifications in the basic geometry of the valve are proposed in order to stabilize the flow. The instabilities are almost completely eliminated by introducing an exergy-destructive element into the design of the valve head and seat.

Introduction

The control valves for steam turbines are located in the steam load between the steam generator and the turbine. They are intended to regulate the flow of steam to the turbine in accordance with the electrical load that is required of the turbogenerator. At maximum valve lift, which corresponds to the nominal operating regime of the steam turbine, the pressure drop caused by the control valve should be small so that the conversion of thermal energy into mechanical energy will be achieved with satisfactory efficiency.

In the case of small lifts, however, pressure drop is inherent to the system, since here the steam is throttled by the valve. This intentional decrease in the generating pressure is produced by viscous friction and by an increase in entropy through shock waves that are often unstable. The increase in the power of generators combined with the limitation on the inlet steam pressure have led to control devices of such dimensions that the problems of flow instability have become critical. They are responsible for:

- vibrations, in particular in the moving parts, which can lead to stem ruptures;
- additional stresses on the nozzles and the blades of the control stage;
- excessive noise that can reach or even exceed acceptable levels.

By way of example, it can be pointed out that the power lost through throttling in the six valves of a 1000 MW steam turbine can attain 130 MW at medium lift. Fortunately, only a part of this lost energy is transformed into vibration and noise. To analyze the mechanisms of these flows with the aim of stabilizing them, it is essential first to study them experimentally, since their complexity makes it impossible to set up a theoretical mathematical model. The mechanical problem of absorbing the shock to which structures are submitted under aerodynamic excitation is not dealt with in this study, which limits itself solely to the causes of and remedies for aerodynamic instability.

Steam is somewhat complicated to use in such tests. The difficulty is due to the formation of condensation waves after the steam crosses the saturation line, when, of course, conditions for expansion in the valve permit it. These conditions, which sometimes exist, would introduce an additional parameter that it was not judged essential to reproduce in order to understand the phenomena and find ways to counteract their effects. Therefore, the experiments were carried out using air. Finally, the supply elbow of the valve, which certainly has an influence on the phenomena being studied, without, however, altering them radically, was simplified. The wide variety of internal shapes used in industry would have increased the quantity of the experimental research considerably. An axisymmetric aerodynamic model is particularly useful in measuring the forces that act on the valve head. A two-dimensional model provides a means of visualizing the different internal flow patterns that are encountered and of observing the abrupt transitions from one flow to another. The compilation and synthesis of the experimental results are used to provide an initial interpretation of the observed phenomena.

The complete elimination of the divergent part of the nozzle, which is formed by the valve head and its seat, will improve the control valve's performance noticeably with regard to flow instability. The effectiveness of this modification has been proven in actual operating conditions. Nevertheless, instabilities are still present. Therefore, the effort to understand the complex and violently changing phenomena that occur in control valves has been pursued. By first making it impossible for the sheet of supersonic jets coming from the valve head to flow together, and by then eliminating the new instabilities created by the abrupt enlargement that has been introduced, it will be possible to propose a new geometry for control valves that will improve their performance decisively. The proposed design will produce significant energy losses in the fluid for small lifts without causing instability, and it will not create any problem at lifts where the valve must be very permeable.

Finally, it should be noted that in the customary classification of a single-phase fluid, the flow being studied is unsteady, three-dimensional, viscous, turbulent, and compressible.

The problem at the industrial level is therefore extremely complex and no claim is made to having solved it analytically. The only goal has been to make a contribution to the search

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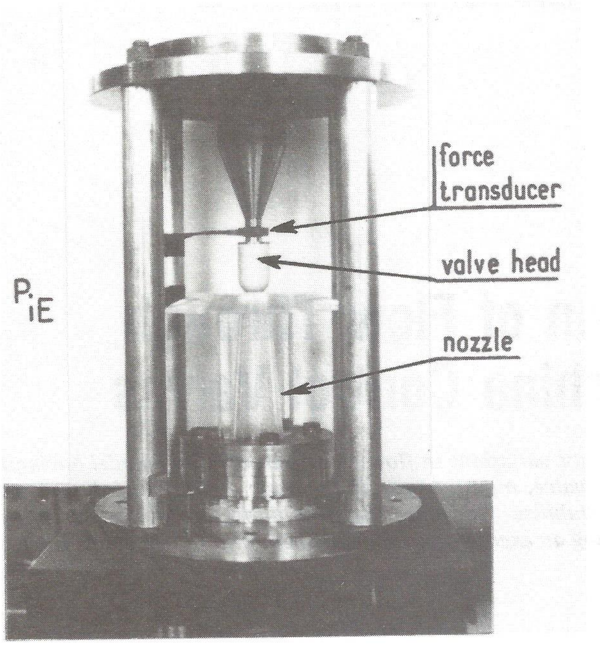

Fig. 1 Axisymmetric model

for a satisfactory technical solution for the short and middle term.

Problem Definition

Experimental Observations. These observations were made on either an axisymmetric model or a two-dimensional model that permitted visual observation of the flow. The axisymmetric reference model consists of a transparent valve body and a hemispherical valve head that is rigidly attached to the valve body (Fig. 1).

Both manufacturers and users have noted that this design produces serious flow instability and is prone to operational malfunctions. A force transducer is placed between the valve head and the nozzle support. This detector measures unsteady forces along the axis of the valve head and perpendicular to this axis. This model functions with a wind tunnel including an air tank downstream. Before the test, a vacuum is created in this tank. The experiment runs long enough so that the flow instabilities studied here occur under steady-state conditions. As the atmosphere is the upstream reference, the inlet conditions are excellent. Although the unsteady force acting along the axis of the valve are also very significant, only the forces perpendicular to the axis are chosen as an illustration of the problems.

In the lift-pressure ratio performance data, two humps of unsteady forces are observed. These two humps have also been observed by Khanin (1975). The axisymmetric model can also be equipped with a piezoelectric meter installed in a Wheatstone bridge, which can monitor the average force along the axis of the valve. This measurement is extremely instructive, as it shows that the hump appearing at the highest expansion ratios corresponds to a jump in this average force. At this stage of the research, it becomes necessary to observe the flows visually in order to describe them as accurately as possible. This can be accomplished by using hydraulic analogies or by viewing them on a two-dimensional model with a schlieren system (Pluviose, 1975).

It is incorrect to replace a three-dimensional flow with a two-dimensional flow by assuming the real valve to be a slice passing through the axis of symmetry. This arrangement no longer shows the flow in a valve: It shows a different flow, with different geometric limits, which has no apparent industrial application. The knowledge that can be gained from such schematizations must be used with caution. Once this warning has been made, however, the advantage of such a configuration for the researcher should be noted. The model, whose shape is derived from the preceding hemispheric valve, is connected to the atmosphere upstream and downstream to a vacuum vessel powerful enough to produce supersonic flows. A quick-closing valve located in the lower part of the circuit is opened at the beginning of the experiment, and the tank fills in a few minutes with air drawn through the model from the atmosphere.

The lift is maintained constant during the trial, and the expansion ratio across the model thus varies continuously. In the lift-pressure ratio field, it is then possible to photograph and film the different flow pattern images. Three distinctly different patterns are observed in the performance field. They are shown in photographs 2(*a–c*).

In photo 2(*a*), taken at high expansion ratio ($P_{iE}/P_{iS}=5$; $L/R=0.4$) supersonic flow can be observed in the second nozzle with nearly straight recompression shock wave. The passage from the pattern seen in Fig. 2(*a*) to the one in Fig. 2(*b*) is violent and corresponds to the second nozzle's cutting out when the expansion ratio decreases. Supersonic jets and their wave trains coming from the first nozzle, which is formed between the valve head and valve seat, are visible in Fig. 2(*b*). These two wave trains become particularly unstable between photos 2(*b*) and 2(*c*), and disappear when the expansion ratio continues to drop, but the jets remain dissymmetric (Fig. 2*c*: $P_{iE}/P_{iS}=2$ and $L/R=0.1$).

These two sudden changes in flow revealed in the flow pattern photographs seem to show that the same thing is occurring here as in the three-dimensional trials, where two humps of stress were recorded.

Possible Causes of Instability. Several causes of instability have been recorded by Pluviose (1984); the list is not exhaustive and certain of these causes are still unconfirmed. Nevertheless, it is known that:

- under certain conditions, and for different expansion ratios, oscillations in the flow through a convergent-divergent nozzle are observed;
- two convergent-divergent nozzles operating in series can, in certain cases, create a type of instability classic in double-throated nozzles. A pumping action accompanied by strong pulsations of pressure occurs during the filling and emptying of the space between the two throats. In a supersonic wind tunnel there is no question of reducing the volume between the two throats, as this is, in fact, the test chamber. In this case, care is taken never to close the second throat after decompression without leaving an adequate margin in relation to recompression. Therefore, no attempt is made to utilize the maximum energy available to avoid the risk of the chamber's returning violently to a subsonic level, which often results in damage. The principle on which a valve operates makes

Nomenclature

Fx, Fy = unsteady force perpendicular to the axis of the valve head (rms value)

L = valve lift

P_{IE} = valve inlet stagnation pressure

P_{IS} = valve outlet stagnation pressure

R = nozzle radius

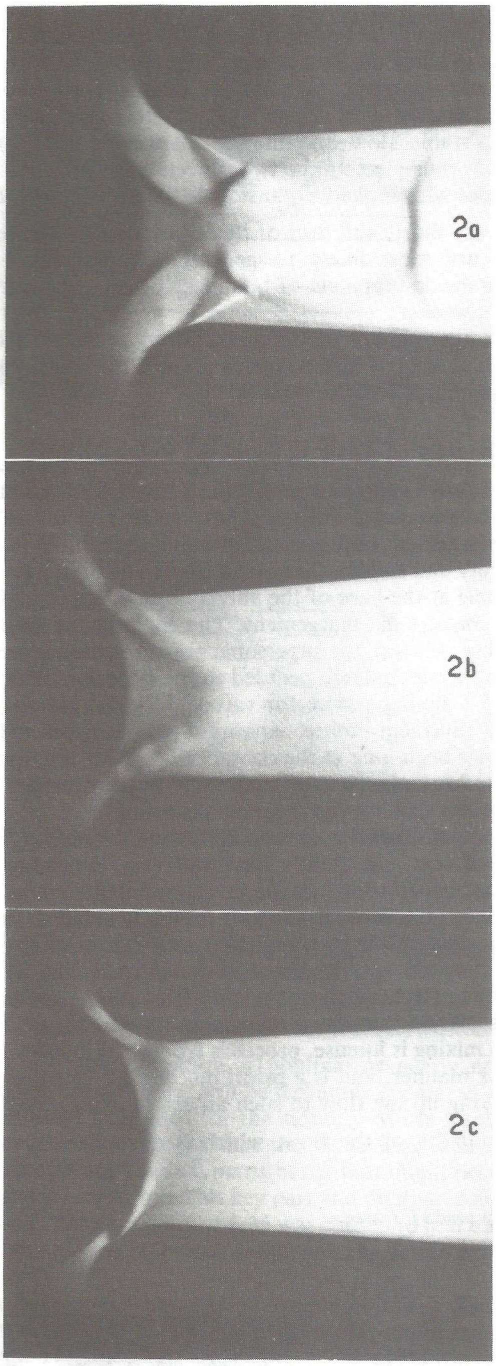

Fig. 2 Flow pattern photographs

recompression inevitable, and thus the diffuser, whose air supply is intermittent and irregular, functions unpredictably.
• two nozzles operating in parallel may also produce very serious instability at times.

As can be seen, the two-dimensional valve is composed of two convergent-divergent nozzles in parallel, followed by a convergent-divergent recovery nozzle. Thus, all the types of instability that have been recorded in the three situations described above may occur simultaneously and render it particularly difficult to make certain observations and interpretations.

A Preliminary Attempt to Stabilize Flow in Control Valves. While all types of instability are not identical in character, they do have the same cause: the divergence of the air stream downstream from the throat between the valve head and its seat. Therefore, in order to eliminate any possibility of recompression (whether subsonic or due to shock waves), a hollow-form valve head in conjunction with a nozzle that is also hollow is adopted (Fig. 3).

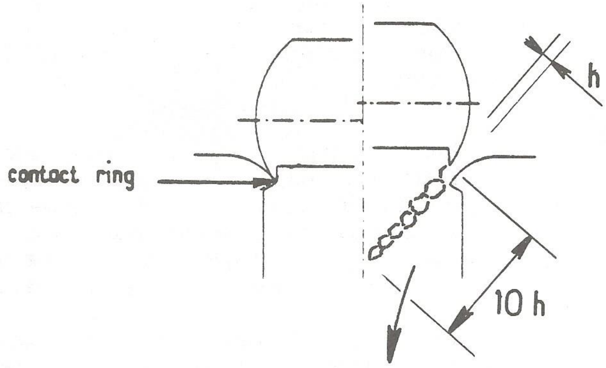

Fig. 3 Preliminary valve geometry to stabilize flow

It would be possible to cut the valve so that the first nozzle would always be appropriate to the expansion ratio. However, it seems preferable to make an even more radical change by hollowing out the valve head from the level of the contact ring or in the area immediately downstream.[1]

Notable improvement in performance was immediately observed as a result of this modification and its effectiveness has been verified in actual operation. Nevertheless, this solution is not totally successful, as instability continues to occur. There is: a possible pumping action on the cavity formed at the base of the valve head; and instability due to the abrupt enlargement that has been created.

An effort must now be made to deal with these two new types of instability in order to be able to stabilize the flow further, once the second throat is eliminated.

Influence of Jet Angle. The lifespan of a supersonic jet is equal to approximately 10 to 20 times the diameter of the exhaust. By applying this fact directly to the problem of valves, it can be seen schematically in Fig. 3 that above a certain lift the jets may meet along the axis.

When these confluent jets meet at the center, they form a sheet (three-dimensional in a real valve) that isolates the cavity created at the base of the valve head from the downstream flow. This sheet creates a depression by viscous entrainment in the cavity formed, and this, in turn, deforms the sheet. When the deformed sheet has created a vacuum that is incompatible with its capacity to resist the infiltrations of the higher-pressure fluid downstream, the sheet ruptures, and there is a return to the initial conditions. The cavity is then emptied once again and a new phase of instability begins.

A systematic study of the conditions surrounding the appearance of the pumping action was not undertaken. It was thought preferable to vary the angle of the flow by changing the valve radius.

The experiments show that indeed, the jets created by hemispherical valve heads with small radii have much less of a tendency to flow together, thus limiting the possibility of a pumping action on the cavity at the base of the valve head. In order to limit the instability due to the confluence of the streams, the hollow valve head must be abandoned in favor of an inward-sloping valve head, which may or may not be hollow depending on the design of the control device.

This solution reduces to a minimum the possibility of the valve's base being isolated from the downstream flow and thus

[1]Patent CETIM—Electricité de France.

improves performance by eliminating the interference of the jets. It should also be noted that the flow does not have the possibility of separating from the valve head before reaching its base. Keller (1980) has observed that this solution gives satisfactory results.

Instability Due to Abrupt Enlargement. Observations made both in actual operating conditions and in the laboratory show that hollowing the valve and the nozzle can result in notable improvement in performance as long as the cavities are not excessively large. Experiment shows that the stability of the valve is jeopardized when the cavity is too large.

In order to stabilize flow as fully as possible, more detailed studies had to be carried out on abrupt enlargements, as there were new ideas to be explored in this area. Particular attention has been given to this and the essential results are summarized below. In the case of a compressible fluid, the basic problem is created by the underexpansion of the supersonic flow between the sonic section at the end of the orifice and the downstream section. The consequence is a flared airflow, generated by a system of infinitesimal expansion waves coming from the edges of the orifice, which creates, at the moment it intersects with the downstream cavity, an organized system of oblique shock waves that is destroyed farther downstream by more or less steady pseudoshocks. It can be shown experimentally on a two-dimensional model that the airflow is disymmetric for low expansion ratios, where it is flattened against one of the walls (Fabri and Siestrunck, 1955). When the expansion ratio rises, the supersonic stream flares, and eventually it flattens against the other wall as well. This is the sudden change in flow (or start in this text), which is preceded by more or less violent disturbances related to geometry of the abrupt enlargement.

In order to stablilize the fluid stream and significantly decrease the quantity of usable energy in the fluid, the device shown below was designed. It is seen here (Fig. 4) for two-dimensional enlargement (Pluviose, 1984).

Supersonic nozzles with limited or no expansion area are placed on each side of the central supersonic stream. They are fed in the same way as the central stream and designed in such a way that a recompression shock wave (shown in the diagram as a straight shock wave) is formed before the throat of the nozzle. As the flow is subsonic behind this shock wave, significant differences in velocity are created between the supersonic central flow and the peripheral subsonic flows. The possibility of diversifying the supersonic jets was used. Each of the flows is blocked by a sonic throat. The system that has been created is not an ejector because there is no entrainment of a secondary fluid by a primary fluid. The two flow rates are independent of each other and are determined solely by the dimensions of the sonic throats. The system does not function as well as mixed-flow ejector because one fluid cannot entrain another. There is forced mixing with intense transfers of momentum; such a device is extremely inefficient. By taking care not to allow the flow coming from the nozzles to return to supersonic velocities, the walls are thus isolated from shock waves. The chances of separation and return flow are reduced; that is, stable flow and intense dissipation of energy are achieved, thus meeting the two objectives.

Nozzles with limited expansion areas are chosen because:

- they are short, and thus of obvious interest to industry;
- they are most likely to generate straight shock waves because the development of boundary layers upstream for the shock is weaker;
- when operating at partial load, during recompression they produce clear separations, which reduces the chance of internal instabilities in these nozzles.

Stabilization of Flow in Control Valves

In a control valve, the area ratio is very high for small lifts, which corresponds, unfortunately, to high pressure ratios. This enlargement ratio varies continually according to the lift. Instability and sudden changes in flow (which are particularly noticeable at the base of the valve) must be expected because of the changes in enlargement. The encouraging results that were obtained with the supersonic pressure reducer during the study of abrupt enlargement led to the adoption of modifications of a similar nature for valves[2] (Fig. 5). Notches in the form of divergent limited-expansion-area nozzles are cut into the nozzle beginning at the contact ring. They are distributed in the nozzle and separated from each other by normal nozzles of the same size (on the diagram shown).

Therefore, downstream from the throat formed by the valve head and seat, the fluid's flow will vary depending on its azimuthal penetration into the valve. An intense mixing occurs at the interface between the two flows. It invades, one after another, each of the layers of this stratification. If shocks still occur, they are very localized in the intermediate levels and have little effect, since they are muffled by the predominant viscous effects they have themselves helped to create. This viscous mixing is intense, proceeds from level to level in a very complex manner, and is a priori inaccessible to calculation.

Breaking up the flow to such an extent assures:

- the stability of the flow, which is no longer treated in a

[2]Patent pending, France.

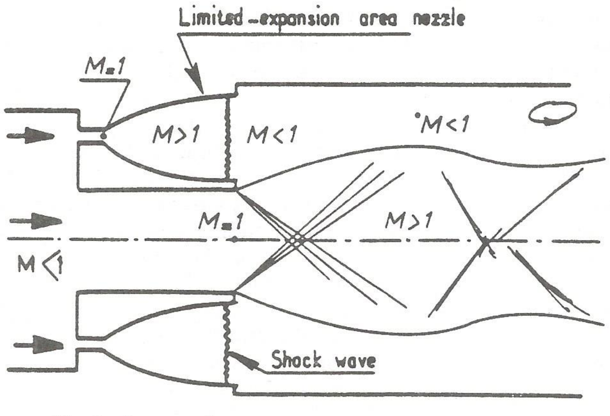

Fig. 4 Supersonic pressure reducer with mixing action

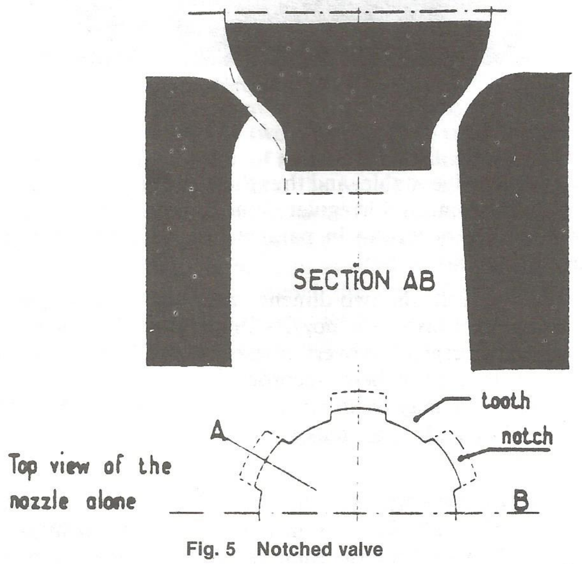

Fig. 5 Notched valve

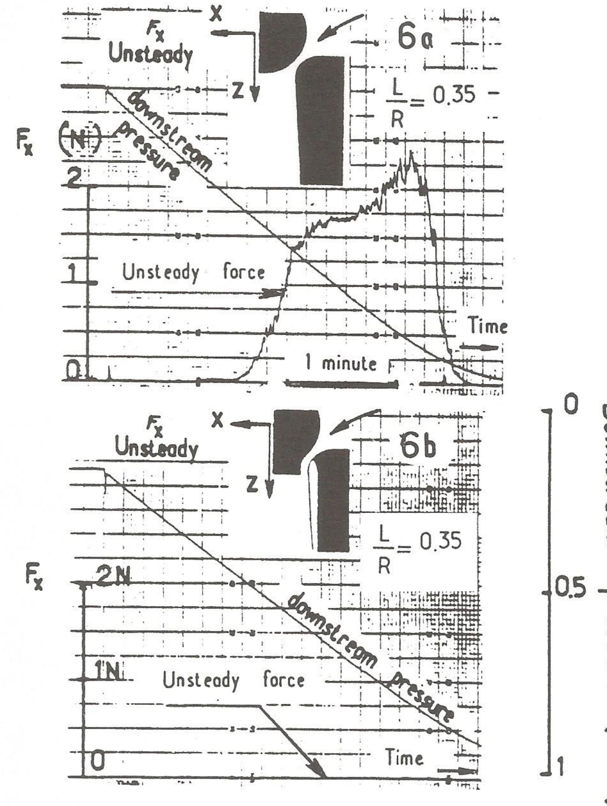

Fig. 6 Comparison of stress along the perpendicular to the valve head axis

single mass. Each micro-instability is destroyed the moment it appears by its immediate environment;

- an efficient mixing over a short distance;
- a flow devoid of any rotation of the fluid downstream.

During subsonic operation at nominal or nearly nominal levels, the notched nozzles will be definitely separated, which is an additional guarantee for the stability of the total flow. Finally, it should be noted that the valve head will not be notched so that any residual perturbance that might occur will be kept at a distance from this key part and dissipated near the fixed nozzle. A reduced lift of 0.35 was chosen to make a comparison between the reference design and the design proposed here.

Figure 6 gives the unanalyzed results obtained during an intermittent-burst test of stress perpendicular to the axis of the valve head. The results are spectacular: The signal transmitted by the detector is negligible in comparison with the signal for the initial design, and this regardless of the lift. The flow in the valves is stabilized. The result that seems the most significant is the following: The decisive improvement was achieved on the first attempt, which is undoubtedly the best justification of the solution chosen.

The utilization of a notched nozzle in conjunction with an inward-sloping valve produces higher pressure losses in the valve's control function, and no instabilities; and does not provoke any disturbance near the nominal operating point of the turbine. Thus, the notched nozzle in conjunction with an inward-sloping valve responds precisely to industrial requirements.

Conclusion

Enormous quantities of energy must be dissipated in control devices. If the walls are not designed to handle the fluid under all operating conditions, the fluid is free to vibrate the structures uncontrollably. Therefore, care must be taken to tame the fluid with simple forms that are adapted to all operating conditions so as to guarantee the reliability of the equipment.

Among the causes of structural vibration that are due to the shape of the fluid flow composed of two nozzles in series, of which one is annular, the following are of particular importance:

- the instabilities created by inappropriate nozzles;
- the violent movement of recompression shock waves from the nozzle onto the valve head;
- the start of nozzles;
- the potential instabilities of annular nozzles for certain expansion ratios;
- the unstable operation of open diffusers;
- the COANDA effects.

Instabilities at the level of the valve may occur simultaneously. They are not devoid of hysteresis and can interfere with the operation of the turbine. They must, therefore, be diminished or eliminated. An initial encouraging step involves removing any possibility of recompression, either subsonic or by shock wave, by eliminating the divergent formed by the valve and its seat. This solution is inadequate to the extent that it creates other instabilities due, in particular, to enlargements when they are too abrupt.

The more or less stable and violent starts in abrupt enlargements, which have been shown elsewhere, can be eliminated by using exergy destructors. An analogous device used in control valves nearly eliminates the unsteady forces on the valve head by organizing the flow in layers which expand at different rates, with intense mixing of these layers during expansion. This solution would seem to be decisive in solving in the short and middle term the problems of internal stability in control valves.

Acknowledgments

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