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I have been requested to contribute to the discussion on the present state of research on reciprocating compressors in Europe. It is a pleasure for me to comply with this request. In view of my specialized activities I have chosen problems which concern the process of compression and the action of valves in connection with the dynamics of gas in a pipe. I am aware, however, that, even in the confined field of my working activities, it is difficult to inform objectively, for access to information varies considerably. It is all very well to talk about the activities of sections with which one is in personal contact but it is more difficult where information is obtained only from publications and there is doubtless also a great amount of valuable knowledge which has not been published for various reasons or which has escaped one's attention. Therefore please excuse my restraint in the judgement of the present state.

In any case, the opinion of the present state of research as well as of its future trend of development is a subjective opinion which is likely to be supplemented or amended, in many respects, both by introductory contributions and also by a number of expert contributions to the Conference.

The primary impulse which led in the past to a systematic study of pressure pulsations in the pipework of reciprocating compressors was provided chiefly by failures of pipework and valves. Similarly as in the United States also in European countries methods of calculation or analogue models were produced with the contribution of which these difficulties could be overcome. In predominant measure the matter in question was the treatment of a non-stationary flow of gas through a pipe for known boundary conditions. Even though the solution was only approximate and was based, in most cases, on the wave equation or on the so-called telegraph equation, the results obtained were sufficient for an explanation of the great majority of failures and they led to the correct remedial measures.

A question which, perhaps, also already belongs to the past is the fairly frequently discussed one whether the problem of pressure pulsations should be dealt with by numerical methods or by analog computers. Practice has shown that analog equipment has a number of advantages consisting, above all, in lucidity and flexibility when changes are being made, but it is more costly. It has therefore proved its worth where a continuous utilization of the actual equipment as well as of the corresponding group of specialists could be expected.

An extensive analog equipment for the modeling of piping systems was built in the Soviet Union and, as far as I know, analog computers built for this purpose have been working for a number of years also in Italy, in Switzerland and in other European countries.

Concurrently with analog computation also numerical methods were developed and the fitting-out of works with automatic computers, by now already a matter of standard practice, has in many cases been made use of for the calculation of pressure pulsations. This method was chosen also in our country.

Thanks to the technique of computation the most serious difficulties have, at present, already been eliminated. The calculation of pulsations in piping systems has become a matter of routine and the substance of further development in this field is now being transferred to universities and, in socialist countries, also to government research institutes.

However, by this statement I do not mean to create the impression that everything of importance has already been done and what follows is merely an academic matter with a limited effect upon practical work. Such an opinion would not agree with reality. A mere comparison of results obtained experimentally with calculated values shows that the number of simplifying assumptions, in particular the assumption of "acoustic waves", is the cause of considerable inaccuracies and does not justify complacency on our part.

Much still remains unclarified, even from the point of view of current practice. We can now determine fairly well the behaviour of pressure pulsations in simple piping systems but the calculation becomes problematic as soon as the piping system consists of members of intricate shapes. Fortunately, however, intricate shapes result, as a rule, also in considerable damping and thus a high level of pulsations is usually not the rule in such systems and failures also are not frequent.

Many unclarities are related to the judgement of the level of pulsations. With the pipework of reciprocating compressors it is common practice to indicate their permissible value as the amplitude of the relative pressure variation. These figures are often also a part of the contract for the delivery of the equipment. Up to that point everything appears to be in order. This, however, it ceases to be as soon as the real level of pulsations is to be determined, for, apart from laboratory cases, only pressure variations can be measured, but they are only one component of the energy of pulsations. The second component, i.e. speed variations, is very difficult to measure in practice and since the level of pressure variations depends, to a great extent, on the point of measurement, reliable data on the level of pulsation of the whole piping system are obtained only at the closed ends of the pipework where the speed is zero.

On the assumption of one-dimensional propagation of waves in a pipe the actual level of pulsations can be determined by simultaneous measurement at two or three points in a section of the pipework of constant cross section. In Czechoslovakia a method is used which permits, on the basis of such a measurement, the determination, of the magnitude of a progressive as well as a stationary wave and of the point of maximum and minimum amplitudes for the chosen number of harmonic components of the oscillation being measured. For current use it is, however, rather complicated.

No less complicated is also another method, that of confronting the measured values with the theoretical calculation and of modifying the input data for the calculation in such a way that the required agreement is reached. It is then assumed that the calculation is correct not only at the points of comparison but also in all other parts of the pipework.

Unless it is desired to judge the level of pulsations, whether calculated or measured, only according to directives or a contract the next question which arises is how high a level of pulsations is, in fact, permissible. The question may be put also differently. At how high a level of pulsations will the compressor equipment still be capable of safe operation? And here the answer is already very difficult. When it is desired to ensure reliability in operation the level of pulsations can be reduced to a minimum by the use of bulky dampers. However, such a solution is bound to be rather expensive and the possibility exists also of a second, no less costly extreme, that of achieving reliability of the piping system by heavy anchoring. In this case pulsations then need not receive so much attention. Both cases may thus serve as a graphic example of the fact that the same aim can be achieved by more than one method and also of the fact that the optimum solution is usually a compromise.

Reality is, however, more complex still. Reliability in operation of pipework is not solely a question of the level of pulsations, i.e. of the magnitude of the driving forces and of the anchoring of the pipework, but also of further factors as, for instance, the effect of the precision of fitting, etc. A number of cases are known from actual practice of fatigue fractures of pipework having occurred as a result of a high fitting prestress even at a low level of pulsations and very low dynamic stresses.

When all this is considered it is not surprising that present opinions as regards the permissible level of pulsations differ widely. When it is expressed as the ratio of the amplitude of the pressure variation to the mean pressure it is stated to be 1% to 3%, sometimes even more. The level of pulsations in valve chambers is usually, however, substantially higher.

Similarly as in the case of piping systems an impulse for development in the study of the effect of pulsations on the working process of compression was provided primarily by failures, in this case of valves. In the removal of their failures the creation of analytical models was used to advantage on a large scale. Well known is the historical development of the technique of modeling by means of which the action of valves was observed at the beginning in dependence on the working process and which was later extended to include further factors. In 1968-69 an analytical model was developed in Czechoslovakia which treated, in a comprehensive way, the processes in the working space, the flow and the dynamic properties of valves, as well as the non-stationary flow of gas in the connected pipework. The aim of this method of work was to prove the relation between pressure pulsations, the course of the working process and the action of valves. The results obtained confirmed the experience known already from actual practice that pulsations not only may, under certain conditions, be the cause of facture of valve plates but may also have an unfavorable effect on the compression process itself.

Therefore further efforts were applied in Czechoslovakia to the suppression of the level of pulsations, particularly in valve chambers and the adjacent pipework. However, to attain this goal it was no longer necessary to use such complicated analytical models. The application of the perforated tube is one of the results of this research.

A similar aim is that of theoretical and experimental research in the USSR, which has been engaged in the development of dampers with internal insertions. The goal was to achieve optimum parameters from the point of view of efficiency and losses as well as of production.

The development of a complex analytical model has received a great deal of attention in England and Scotland. The analytical model of a compressor with pipework was developed further, the mutual relation for the connection of two working spaces to a single piping system at a phase displacement of the work cycle was determined, and further influences, such as friction, heat interchange, etc. were included in the calculation of a non-stationary flow through a pipe. The results obtained have proved very good agreement between theory and experiment.

Noteworthy results in the development of a complex model were achieved also in Holland. The work is interesting by the fact that a hybrid computer was used for this model.

In connection with the action of pulsations on the working process of the compressor the possibility was studied in the Soviet Union of achieving an increase of the output by means of tuning of the suction pipe. The results obtained were very interesting as, for instance with a double-acting compressor, an increase in output of as much as 14% was reached. This problem was studied similarly also in England, Scotland and Czechoslovakia. Theoretical reflections as well as experiments have proved that it is really possible to increase the output of a compressor in this way. Unfortunately the increase in output thus obtained is paid for by a considerably higher power consumption. In this respect reciprocating compressors differ to some extent from internal combustion engines where the effect of tuning is of very great importance for the output of the engine as well for its working efficiency, in a positive way. In discharge pipework pulsations are always undesirable. The gain which can be achieved by evacuation of the clearance space is insignificant.

I have mentioned in my contribution several problems the solution of which from the point of view of the present development in the field of dynamics of gases in the pipework of reciprocating compressors I consider important. To foresee in which direction development will continue is not easy. If, however, we look back upon the development of the modeling technique, it will become apparent that the treatment of problems proceeded from simple dependences to increasingly involved models. Present analytical methods are capable of encompassing the entire complex from the working space in the cylinder through the valves to the dynamics of the pipework. They are therefore capable of dealing with the technical side of the problem in its full scope.

However, the problem that has not been solved as yet, one that in actual practice, is important in deciding on the technical solution, is economy.

To create complex models which would take into account these points of view as well is not likely to be easy, for the quantities involved are very heterogeneous. Even though there are already indications of such a solution, e.g. of the modeling of the effects of pulsations on the specific power consumption, etc. It is, for the time being, difficult to say how such a model should be developed. I am convinced, however, that this problem, too, will be successfully mastered, for it is highly necessary and purposeful to do so. Not only now but also in the future one of the decisive criteria of every compressor equipment will be how cheaply it is capable of producing compressed gas.