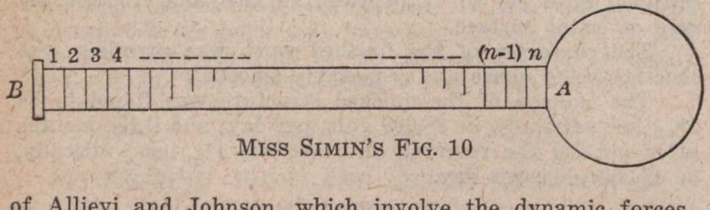
PRESSURES IN PENSTOCKS CAUSED BY THE GRADUAL CLOSING OF TURBINE GATES*

By Otto V. Kruse
Hydraulic Engineer, Larner-Johnson Valve & Engineering Co., Philadelphia, Pa.

THE writer has studied the phenomena of water-hammer, and offers a short analysis of Miss O. Simin's translation of Prof. Joukovsky's notable work, and an elaboration of certain parts of Mr. Gibson's paper.

Any pipe under pressure and containing water in motion may be assumed as a unit of energy under a condition of equilibrium. If we wish to stop the column of water, it means the application of a certain amount of force during a certain time to bring about the conversion of energy and restore the equilibrium. In analysing the phenomena which take place, the writer believes that the most important point to study is the rate of destruction of velocity as affected by the net head, because this determines to a large extent the rate of pressure rise and hence the maximum pressure rise. Apparently, Allievi used this as a basis for the development of his formula, and this, of course, applies to Johnson's formula, which is the same as Allievi's. Any formulas, such as Warren's and Vensano's, which do not take this into account, must be incorrect, except for one set of conditions. The curves given by Mr. Gibson show how far from the truth they may be.

In accordance with the ordinary methods of integration, it may be considered that the gate movement throughout the duration of the stroke is made up of an infinite number of small instantaneous movements. In the case of the formulas



Miss Simin's Fig. 10

of Allievi and Johnson, which involve the dynamic forces, each little movement of the gate produces a pressure:—

$$h = Ldv/gdt$$

The conditions existing, then, at the end of any small movement are:—

1. The original velocity has been decreased by the amount of the velocity destroyed during this first movement;

2. A dynamic pressure has been created due to the destruction of velocity.

A new velocity now exists, which is dependent, not on the original net head, but on a new head made up of the original net head and the dynamic head. As brought out by Mr. Johnson, these curves of dynamic pressure-rise and decrease in velocity may be calculated by a simple method of arithmetic integration, using only the relation, $h = Ldv/gdt$. The Allievi or Johnson formula will give a figure for maximum pressure rise, and Mr. Johnson has also developed a formula for the shape of the pressure curve, these formulas giving the same results as can be obtained approximately by arithmetic integration.

The question to be considered now is: To what extent, and how, do the compressibility of water and extension of the pipe walls affect the pressure and velocity curves? We know that, as the time of closing grows shorter, the Allievi formula approaches infinity. On the other hand, Joukovsky proved that the maximum pressure which obtained for instantaneous closing depended on the velocity destroyed and the speed of propagation of the pressure wave, and could not exceed "maximum water-hammer." It is not difficult to see that, for a long closing time, the compressibility of the water and extension of the pipe walls have very little effect on the maximum pressure, but, as the time of closing grows shorter, the properties of the materials have a greater and greater effect. The writer believes that Mr. Gibson's formulas have successfully supplied this missing gap between Allievi's and Joukovsky's theories, and serve to give correct results for all conditions.

Professor Joukovsky made a great many experiments to determine the magnitude of maximum water-hammer and the speed of propagation of the pressure wave, all based on instantaneous closing of the gates. The details of the experiments will not be given here, but the following is a synopsis of the theory, taken verbatim from Miss Simin's translation:—

"In Fig. 10, let *A B* be a pipe, in which water flows with velocity, *v*, from the origin *A*, past the gate *B*. If, now, the flow is suddenly stopped by a rapid shutting of the gate, *B*, the kinetic energy of the water column, *A B*, will cause an increase of pressure in the pipe.

"Let us consider the column of water, *A B*, as divided into *n* very small equal sections, 1, 2, 3,.... (n—1) and *n*.

"The phenomena of water-hammer take place in a series of cycles, each consisting of four processes, as follows:—

"(1) Section 1, meeting, in the gate, an obstacle to its movement, will be compressed and will stretch the pipe wall surrounding it. All the kinetic energy of this section of water will be used up (*a*) in its own compression, resulting in the increase of pressure by an increment, *P*, and (*b*) in the corresponding stretching of the walls in section 1 of the pipe. As a result of this action, section 1 of the water column has left vacant behind itself a small space, to be occupied by a part of the next arriving section 2. Consequently, it is only after section 1 has been stopped and compressed, and after the small space thus left has been filled, that section 2 can be arrested and compressed.

"Now the kinetic energy of section 2 must be expended in some way. Will it increase the pressure upon the gate, which has already been caused by the arrest of section 1? No, and for the following reason:—

"The pressure upon the gate depends entirely upon the pressure, *P*, sustained by section 1, which is now in static condition.

"The pressure upon the gate could therefore be increased only if section 1 could be farther compressed, and this could take place only if the pressure upon the surface between it and section 2 (which we may imagine to be a thin piston) could be greater from the side of section 2 than it is from the side of section 1; and this is impossible, because section 2 has only the same kinetic energy as section 1, and this energy will (as in the case of section 1) be used up entirely in compressing the water of the section (section 2) only to the same additional pressure, *P*, and in stretching that part of the walls surrounding section 2.

"The same is true of each following section, 3, 4,.... (n—1) and *n*; each of these sections, as it is arrested, being compressed to pressure, *P*.

"During process (1) a small quantity of water flows from the reservoir into the pipe, to occupy the space formed by the compression of the water and the extension of the pipe walls.

"Finally, when all the sections have been arrested, the entire column will be under the pressure, *P*. The entire energy of the water column is now stored (as potential energy) in elastic deformation—viz., in the compression of the water column and in the extension of the pipe walls.

"But this condition cannot be maintained; for

"(2) As soon as the additional pressure, *P*, has been produced in the last section, *n*, the water in that section will again expand, and the walls of that section of the pipe will again contract, restoring the original conditions in that section, and pushing the water of that section back into the reservoir from which the pipe issues, and restoring the original normal pressure in section *n*.

"The operation will now be repeated by each section (n—1),....4, 3, etc., in turn, until all the potential energy, stored in the water column when it was under the pressure, *P* (neglecting the portion lost in friction), has been reconverted into kinetic energy.

"During process (2) the water which entered the pipe during process (1) is forced back into the reservoir.

*Discussion (presented to the American Society of Civil Engineers) of Norman R. Gibson's paper (see September 4th and 11th issues of *The Canadian Engineer*).