Discussion

Steam-Turbine Leaving Losses and Vacuum Corrections[1]

Ernest L. Robinson.[2] Professor Helander has presented a detailed set of computations of the effect of leaving velocity at the wheel annulus on vacuum corrections for steam-turbine performance. The corrections are based, as they should be, on a particular known performance and the author wisely qualifies his methods as suitable for use in the field where manufacturers' corrections are not available, and his basic theoretical analysis of the steam action in the last-stage bucket exit seems to be correct.

There are, however, a number of influences that must be taken into account in preparing the vacuum corrections for steam-turbine performance. The most important of these is the leaving-velocity loss from the last-stage wheel and this he has considered. Another important element is the pressure drop through the exhaust hood from the wheel annulus to the exhaust flange, which occurs despite considerable excess area. These two influences are closely inter-related and only an approximate analysis of the actual leaving loss can be made without taking account of the variation of pressure due to drop through the hood. Omitting the exhaust-hood loss, however, does give a first approximation to the vacuum corrections since when the exhaust-hood loss is larger, the leaving loss is less. Certain upstream effects are also to be reckoned with for a stage or two preceding the last, particularly at light loads. We understand from the author that these latter effects, while not evaluated, are allowed for in Appendix B if certain factors are known.

Manufacturers' vacuum corrections attempt to evaluate all these influences with the best available knowledge as to the performance of the several elements, supplemented with empirical corrections to the theoretical calculations following analyses of many actual tests. It would be our recommendation that where important decisions are involved, actual tests at various vacuums be carried out or the manufacturers' vacuum corrections, which are based on a wide knowledge of such tests, be used.

C. Harold Berry.[3] The determination of vacuum corrections is an important undertaking in connection with an acceptance test of a steam turbine. The A.S.M.E. Test Code for Steam Turbines now requires that vacuum corrections be established by prior agreement between the manufacturer and the purchaser, either in the purchase contract or in a separate agreement, or else that the corrections be found by auxiliary tests. The first alternative is tantamount to accepting the manufacturer's correction curves; if the purchaser is unwilling to do this, he must conduct a costly series of tests.

Some readers may be of the opinion that Professor Helander has developed another method for securing the desired corrections that will avoid the difficulties of the foregoing alternatives. That this is not the case seems evident from the fact that items 2 to 6 and 28 in the table on page 154 of the original paper are stated to rest upon information furnished by the manufacturer. In the case of a test, item 5 would be known from the test results, and some of the other items might be obtained by sufficiently skillful measurement; but in the end the computed results will rest upon data furnished by the manufacturer and accepted by the purchaser. If the purchaser is willing to accept basic data, he will probably be equally willing to accept the final result. Thus it appears to me that this method should not find a place in the A.S.M.E. Test Codes.

The writer speaks as chairman of Power Test Codes Individual Committee No. 6, which is now engaged in the revision of the Test Code for Steam Turbines. He does not, however, speak for the Committee, since there has been insufficient time for a poll of its membership.

John A. Dent.[4] Both designers and users of turbines will find Professor Helander's paper useful in the estimation of leaving losses and vacuum correction. The influence of critical speed and the limitations of possible vacuum at different loads are clearly brought out. While at first glance the procedure seems rather complicated the development is entirely logical and with a little study and practice can be applied with a reasonable expenditure of time and work.

The problem of determining leaving losses is exceedingly complex, and many variables enter its solution. The author is careful to point out that his method gives only a reasonable approximation and calls attention to some of the neglected variables which may influence the result, namely, leakage, moisture, and variation in nozzle efficiency. Other items which might be mentioned are:

(*a*) Variation in leaving velocity across section of jet
(*b*) Variation in leaving velocity from root to tip of blade
(*c*) Variation in gaging from root to tip.

Under (*a*) it should be remembered that the discharge varies as the mean velocity across the jet, while the kinetic energy varies with the "root mean square" of the velocity. Ordinarily the error in using mean velocity for computing kinetic energy is quite small.

The error in computing kinetic energy from the leaving velocity at mean-blade speed may be considerable in some cases, and entirely negligible in others. For example if the tangential component of the relative velocity is equal to the mean-blade speed, the absolute velocity leaving is a minimum at the middle of the blade, and increases both toward root and tip. If the kinetic energy is calculated on the basis of the velocity at the middle of the blade the result will obviously be too low. In the accompanying diagram, Fig. 1, OA is the relative velocity, AB the mean-blade speed, AC the root-blade speed, and AD the tip-blade speed. Then OB is the absolute velocity at the middle of the blade, OC at the root, and OD at the tip. Plainly, the mean leaving velocity is greater than OB.

The writer made a few calculations on the magnitude of this error using as an example a two-foot blade mounted on a six-foot drum revolving at 1800 rpm. A straight blade was assumed with

[1] Published as paper FSP-57-8, by Linn Helander, in the May, 1935, issue of the A.S.M.E. Transactions.

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a constant gaging giving sin α = 0.45. The figures chosen correspond to a mean-blade speed of 754 ft per sec and a tip speed of 942 ft per sec.

At a relative velocity of 850 ft per sec the kinetic energy was 108 per cent of that found by assuming the leaving velocity corresponding to the mean-blade speed. At 1000 ft per sec the ratio dropped to 103.4 per cent and at 1270 ft per sec became 100 per cent. A maximum of 115 per cent was found at 582 ft per sec.

No attempt has been made to evaluate the effect of change of gaging from root to tip. Such an investigation would require a

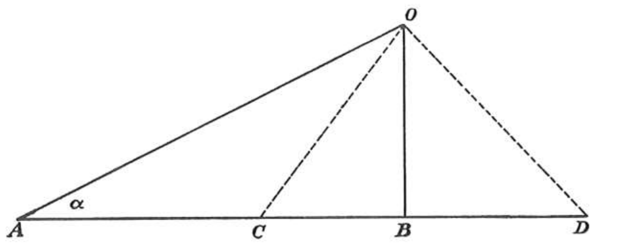

Fig. 1

detailed study of the design of blading used in any individual turbine. Such procedure is far beyond the intended scope of the author's paper. The writer wishes merely to call attention to this factor as one of the variables whose influence has been neglected.

The determination of the critical conditions is one of the most interesting and important contributions in the paper. The curves and approximate formulas developed by the author will do much to save time and labor in this calculation. The data supplied are almost the exact reverse of those given in impulse-turbine nozzles. There a nozzle of given dimensions is supplied with steam of known pressure and quality, and the discharge is easily computed. In the present instance a given discharge is delivered at a known pressure, but unknown quality, and the critical conditions have to be found. A method of successive approximations is used. The author shows that a correct solution is quickly reached. In fact the first approximation appears to be well within the limits of accuracy of the method, but the author properly refuses to take this for granted and carries through the second approximation, showing that his first assumptions were close to the truth.

The writer wishes to express appreciation of the paper and to welcome it as a valuable contribution to our knowledge of the turbine.

Author's Closure

The procedure for evaluating steam-turbine vacuum corrections proposed in the paper was prepared principally for use in making economic and heat-balance studies of the kind usually undertaken before the purchase of turbines and condensers to determine among other data, the vacuum which probably would be the most economical and, therefore, the approximate vacuum for which the turbines and their condensers should be designed.

In view of the uncertainty of data other than vacuum corrections, such as cost data and load curves, which must be estimated or assumed for these preliminary studies, it was felt inadvisable to introduce refinements that might add much to the complexity of the problem of evaluating approximate vacuum corrections and yet have but a small influence on final conclusions. For this reason, and also because precise data on the design of blades and exhaust hoods are not available usually for preliminary studies, the factors to which Professor Dent and Mr. Robinson appropriately call attention were ignored.

Where the necessary data are available and precise results are desired, exhaust-hood losses should be calculated and leaving losses should be more accurately evaluated taking into account, as Professor Dent suggests, variations in gaging from root to tip as well as variations in blade speed from root to tip. When variations in gaging and in blade speed from root to tip are taken into account, the equation for leaving losses takes the form of an integral which can be evaluated graphically if it cannot conveniently be evaluated analytically.

In this connection, it may be well to point out that in evaluating vacuum corrections, two leaving losses calculated for different vacua are subtracted and their errors may be compensatory to some extent. Table 1 of this discussion shows this to be the

TABLE 1 ERROR IN CHANGE IN LEAVING LOSSES ACCOMPANYING A CHANGE IN RELATIVE VELOCITY BASED UPON DATA PRESENTED BY PROFESSOR DENT[4]

Relative velocity, fps	582	850	1000	1100
Approx. leaving losses, Btu per lb	2.48	2.95	4.46	6.00
Error in leaving losses, per cent	15.50	8.00	3.40	1.60
Absolute error in leaving losses, Btu per lb	0.383	0.235	0.151	0.097
Absolute error in change in leaving losses, Btu per lb	Base	0.148	0.232	0.286
	...	Base	0.084	0.138
	...	...	Base	0.054
Error in change in leaving losses, per cent of increment of relative kinetic energy[a]	Base	1.95	1.75	1.65
	...	Base	1.50	1.40
	...	...	Base	1.30

[a] Increment of relative kinetic energy = [(Terminal rel. vel.)^2 — (Base rel. vel.)^2]/50,000.

case for the conditions assumed by Professor Dent. It shows also, for these conditions, that when leaving losses for two different relative velocities are evaluated at the mean diameter, the error in their difference is but a small fraction of the conversion of energy required to accelerate the steam from the lower to the higher velocity, and therefore may be ignored where approximate data are satisfactory.

In the writer's sample calculations, if leaving losses had been evaluated by taking into account variations in blade speed from root to tip on the assumption that straight blades of constant gaging are employed, then the calculated vacuum correction factor, Item 58 on page 155 of the paper, would have changed from 4.60 per cent to 4.67 per cent under Case 1 and from 1.33 per cent to 1.38 per cent under Case 2. For the purposes for which these estimated vacuum corrections are likely to be used, these differences are negligible.

The foregoing considerations do not in any sense detract from the force and value of Professor Dent's criticisms and suggestions. For conditions other than those here investigated the error introduced by evaluating leaving losses at the mean diameter may have a greater effect on the vacuum correction; and as previously stated, where precise values of leaving losses and vacuum corrections are desired, the factors Professor Dent discusses should be considered. The author believes, however, that where the data needed for evaluating leaving losses precisely are not available, his procedure will give approximations of vacuum corrections satisfactory for use in preliminary studies.

The author wishes to thank Professor Dent, Mr. Robinson, and Professor Berry for the discussions they have contributed. Their points of view and criticisms have helped to clarify the intent of the paper and the limitations of the procedure proposed. He agrees with Professor Berry that the procedure outlined for evaluating vacuum corrections should not be made a part of the A.S.M.E. test code.