

overall critical seal pressure ratio as a function of the number of restrictors has been investigated analytically and experimentally by several authors and their findings are quite consistent [11, 13, 14]. The subcritical flow coefficients for an annular restrictor as a function of the restrictor aperture geometry and Reynolds number (or pressure ratio) are relatively well in hand. Vermes [15] successfully applied Bell and Bergelin's [17] test results for water and oil to gases. Snow's coefficients, given in the discussion of [11], cannot be compared directly with those of Bell and Bergelin since one is correlated with Reynolds number and the other with restrictor pressure ratio. However, if plausible assumptions are made concerning viscosity and density it can be demonstrated that the two sets of coefficients are reasonably consistent with each other and of the same magnitude (0.65–0.85) as those found elsewhere [6, 10, 11].

Hence, by using the appropriate mix of theory and empirical data it is possible to quite accurately predict the performance of an "ideal-labyrinth" seal provided rotational speeds are not too high (see Weinberg's discussion of [11]). If the dissipation of kinetic energy is relatively incomplete between throttlings, such a prediction is not possible. Unfortunately the present state of labyrinth seal technology does not permit this effect to be predicted with the same degree of certainty or accuracy as the throttling effect enjoys. From the flow visualizations of Keller [19], Jerie [10], and Groddeck [18] it is clear that the flow field which dissipates the kinetic energy is quite complex. Analytical formulations of the kinetic energy carry-over have been attempted by Hodkinson [8], Groddeck [18], and Vermes [15]. Although the experimental values of the carry-over coefficient reported by Egli [6] and Jerie [10] differ somewhat, it is obvious that the effect can be substantial. Vermes [15] carry-over coefficient is incorporated in his overall correlation of theory with experiment, so that it is not possible to compare the carry-over coefficient directly with measured values. The carry-over coefficient is commonly represented as a function of the restrictor's clearance and pitch distance, and in one case also as a function of the restrictor's thickness [15]. Several investigators have noted, however, that the chamber depth also has an influence. It is thought that the optimum chamber depth-to-pitch ratio is approximately unity (see Foster's discussions of [14 and 10]). Trutnovsky has confirmed the existence of an optimum depth [9]. Since the design of a labyrinth seal is almost always a compromise between the desire to place the greatest number of restrictors in a given space and at the same time have the pitch distance between the restrictors large enough to reduce the kinetic energy carry-over to a minimum, an efficient configuration can be attained only through the proper proportioning of all dimensions. Until the chamber dissipation process is better understood it will not be possible to develop a rational basis for optimizing seal performance subject to the opposing geometric constraints described above.

A recent revival of interest in the phenomenological models of internal tubulent flows by Spalding [20] and his colleagues offers some hope that this important but complex turbulent flow may yet yield itself to direct analysis via computer codes. Should the problem yield to these methods, a major breakthrough in seal technology will have been accomplished.

Summary

As one author has put it, the thermodynamics of labyrinth seals is well understood, but much remains to be learned about the

basic fluid mechanics of labyrinths. This is particularly true of the dissipative processes which convert kinetic energy to thermal energy within the labyrinth's chambers. Until this gap is filled, decisions regarding sizing of the chamber depth and width or restrictor pitch will continue to be made using rough rules of thumb or sketchy empirical evidence. The optimization of design geometry awaits the completion of this final task. Methods are presently being explored which, if successful, may well provide the means for solving this problem.

Acknowledgment

The author is indebted to the General Electric Company whose support permitted him to research the reference material quoted herein. An unpublished 1962 literature survey by Professor W. K. Stair which he kindly sent the author proved quite helpful locating early references.

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DISCUSSION

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The author is to be complimented for the assimilation of a rather complete listing of the pertinent literature of labyrinth seals. The significant value of this type of effort is sometimes

overlooked until one is faced with a new problem that is outside his previous background and experience. The immediate benefit of finding in a single source a "road sign" to previous work is long remembered and appreciated by those of us having been in this situation.

While there are always some dangers in presenting abridged details to previously developed theories, this writer regrets that the author did not make explicit presentations of some of the var-

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ious theoretical models he discusses. In several cases the final working equations are quite simple closed-form solutions whose presentation could have greatly enhanced understanding of the author's description.

The acknowledged 1962 literature survey by Prof. W. K. Stair, while not published in the body of technical journals, was issued as a technical report [21]. This previous effort was supported by the Union Carbide Nuclear Co.

Additional Reference

21 Arnold, F., and Stair, W. K., "The Labyrinth Seal—Theory and Design—A Literature Survey," Mechanical and Aerospace Engineering Research Report No. ME-5-62-1, University of Tennessee, March 1962.

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Mr. Sneck has presented a useful comparison of analytical methods for determining the operational characteristics of labyrinth seals. Labyrinth seals, although essentially unchanged for a number of years, still play an important role in sealing. For high-temperature gases on very high speed equipment, labyrinths often are employed, and any performance improvements will not only conserve energy, but will help solve the problem of noise pollution. We hope that as the author continues his work he will present additional papers correlating analytical analysis with test data and suggesting a total design approach to optimize performance.

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