VI Conclusions

Several general conclusions may be drawn from this study of tip-clearance effects in centrifugal pumps tested in water.

1. The maximum efficiency for all unshrouded impellers tested occurred at the minimum value of tip clearance. The rate of change of efficiency with the tip clearance ratio was different for each of the four impeller models.

2. The efficiency for the RI-1 model unshrouded impeller at the minimum value of tip clearance was higher than for the unshrouded version. A similar trend is predicted from the tip-leakage flow analysis for the RI-15 model impeller at sufficiently low values of tip clearance. The slight increase in the slip correlation plots, the slip increases and the input head coefficient for best efficiency decreases with increasing values of tip clearance. This is attributed to the unfolding effect of the tip section by the leakage flow. The slip for the shrouded impeller agreed most closely with Acosta's prediction.

4. For the RI-1 impeller models, the five-bladed version produced the optimum hydraulic performance. The reduced solidity for the four-bladed version resulted in substantially lower head rise and efficiency.

5. The cavitation performance for the shrouded version of the three different impeller models was consistently inferior as compared to the unshrouded impeller. This suggests possible optimization of hydraulic performance by partially shrouding the impeller.

VII Acknowledgments

The authors wish to express their appreciation to all members of the CANEL technical staff who participated in the various phases of the analytical and experimental programs. This work was supported under various contracts for the Air Force, Navy, and the Atomic Energy Commission as part of the liquid metal pump development programs at CANEL.

References


DISCUSSION

F. G. Hammitt

The authors are to be highly complimented and thanked for this careful documentation and publication in the open literature of their experimental data relating to the effects of tip clearance and shrouding on a set of centrifugal pump impellers for which they have also, here and previously, published much detailed information regarding cavitation performance. Well-organized and correlated data of this type are very valuable to those not having access to comprehensive experimental data of their own.

The formulation of a tip-clearance sensitivity factor based on experimental data is of course very useful in determining the relative advantages to be expected by further reducing tip clearance and has been demonstrated by the present tests to be meaningful in this regard. I think the results are a little more general than is claimed. It is stated in the paper that $C_t$-values can be compared for cases where $\delta/L$, $b$, and $\lambda$ are fixed. It appears to me that $\delta$, rather than $\delta/L$, is to be regarded as fixed, since this is a sufficient condition for $L \alpha C_t$.

The present analysis considers changing leakage as the only effect of varying tip clearance. However, in addition to effects from leakage on blade loading, and its radial distribution, there must also be shear in the fluid between the blade tips and the housing, and this would increase the leakage as is decreased (increasing the power requirement and reducing the efficiency), because of the increased velocity gradient in the clearance space. Hence competing mechanisms are involved. It would appear that a very small clearance, if it were possible to fabricate such a machine, might lead to reduced efficiency (as compared to a slightly larger clearance), since the increased shear, and perhaps other effects, would more than counter the effect of reduced leakage. Thus an optimum clearance would exist. Reduced clearance, in the limit, would of course not lead to a flow regime identical to that of the shrouded case. I would be interested in the authors' comments on this matter.

Finally, I wonder if the prediction of "Stodola's correction" could be included, perhaps in the Closure, on the "slip correlation" plots. Since this is a very easy correction to apply from the viewpoint of the designer, I would be curious to know how it would match the experimental data here presented.

Authors' Closure

The authors wish to thank Professor Hammitt for his interesting comments.

First, with regard to the question concerning the existence of an optimum tip clearance, the analytical model used only attempts to account for the tip leakage flow rate without considering directly any secondary effects associated with tip clearance, such as shear in the fluid between the blade tips and the housing. However, the empirical coefficients $b$ and $\lambda$ derived from experimental data do include the effects of shear flow on leakage. An optimum minimum value of tip clearance may indeed exist, but this has not been conclusively verified for pumps in the literature. E. A. Spencer previously reported on water tests with an 11-in-dia axial-flow pump, which included the performance characteristics for various impeller blade tip-clearance values from 0.6 to 2.4 percent of the blade height. He found that, in general, the efficiency decreased with increasing clearance, confirming the results of the current paper. He also observed some initial improvement in efficiency as the clearance was increased from very small values, but this was attributed to random friction...
losses, and Dr. Spencer felt that further tests would be needed to confirm the existence of an optimum tip clearance for best efficiency.

Secondly, in reply to Professor Hammitt’s question on values for Stodola’s slip correlation, the following table listing shut-off head coefficients computed according to Stodola, Busemann, and Acosta was prepared for different impeller models referenced in the current paper.

<table>
<thead>
<tr>
<th>Impeller Model</th>
<th>Shut-Off Input Head Coefficient</th>
<th>Stodola</th>
<th>Busemann</th>
<th>Acosta</th>
</tr>
</thead>
<tbody>
<tr>
<td>RI-1</td>
<td>0.77</td>
<td>0.78</td>
<td>0.825</td>
<td></td>
</tr>
<tr>
<td>RI-2AX</td>
<td>0.88</td>
<td>0.88</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>RI-4A</td>
<td>0.81</td>
<td>0.86</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>RI-5A</td>
<td>0.73</td>
<td>0.76</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td>RI-6A</td>
<td>0.66</td>
<td>0.72</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td>RI-7A</td>
<td>0.82</td>
<td>0.79</td>
<td>0.845</td>
<td></td>
</tr>
<tr>
<td>RI-15A</td>
<td>0.86</td>
<td>0.83</td>
<td>0.81</td>
<td></td>
</tr>
</tbody>
</table>


It is noted that Stodola’s prediction is only strictly valid for radial-flow impellers. Busemann’s analysis was derived for potential flow in two-dimensional impellers with a finite number of logarithmic spiral blades. Hence Busemann’s theory is also only valid for predominantly radial-flow impellers. Acosta’s slip correlation was derived for flows over conical impeller tip and hub surfaces so that his results are most valid for mixed-flow impellers.

A comparison of the shut-off input head coefficients shown in the foregoing table with the data presented in Figs. 16 to 19 of the current paper shows a scatter of results, although the differences are rather small for most cases. For the RI-4A model impeller shown in Fig. 18, Stodola’s prediction appears most accurate, whereas for the RI-15 model impeller shown in Fig. 19, Acosta’s value is in closest agreement with the experimental data. However, the experimental data show that a considerable variation in the values of shut-off input head coefficient occurs for different values of tip clearance for each impeller tested, and this should be taken into account in the design of unshrouded impellers.