MIX IT UP

Yousef Jarrah, Craig Fennessy, and Tim Smith, Nikkiso Cryo Inc., USA, explain the need for cryogenic mixed-flow pumps in LNG applications.

The LNG supply chain is a long process and, depending on the process phase, the pumping requirements can differ in terms of quantity and quality. In the first phase, natural gas is extracted from the ground or separated from oil through a distillation process. Once captured as gas, it is then liquefied and stored in the producing country. In the second phase, the LNG is transferred onto a ship and stored onboard the vessel while being transported to the consuming country. Finally, upon arrival in the consuming country, LNG is transferred, stored, regasified, and distributed to the end-user.

The product utilised to transfer LNG is called a cryogenic pump. Nikkiso Cryo Inc. (NCI) supplies submerged motor pumps, which perform for up to 50 000 hr without service or maintenance, delivering up to 4000 m^3/hr of LNG, and producing up to 4000 m of head. For applications where the capacity is high and the required head is low, a mixed-flow type pump yields the best performance. This article aims to reveal the hydrodynamic reasons for this.

Engineering challenges

While it is in the interest of all players throughout the LNG supply chain to optimise pumping efficiency, pump design differentiations occur due to variations in required capacity, head, motor power, and net positive suction head (NPSH). This renders the production of different types of single and multi-stage pumps complex for several reasons. A typical pump, with the electric motor submerged in LNG, is shown in Figure 1.

Firstly, the motor and bearings are continuously cooled by the process liquid through secondary flow extracted from the main flow discharge stream. Secondly, a thrust balancing mechanism is used to render the net axial thrust near zero. NCI uses a reliable and robust balance-piston located downstream of the last stage. Secondary flow is delivered into the balance-piston to maintain proper function. Thirdly, for multi-stage pumps with long shafts, an increased number of rolling elements and journal bearings are required in order to stabilise the rotating assembly. Finally, to maximise the efficiency, the hydraulic design must be optimised.

Pump types

For multi-stage pumps, each of the multiple pump stages consist of a rotating impeller and a stationary diffuser, as shown in Figure 1. In addition, a single inducer is deployed upstream of the first stage in order to prevent cavitation near the tip of the first stage impeller. In general, approximately 80% of the head is produced via the impellers, while the remaining 20% is produced via the diffusers and inducer. Therefore, the hydraulic design of the impeller is essential to achieving optimum performance.

Overall pumping efficiency is a function of both motor and hydraulic efficiencies; electric motor action causes rotation, while impeller blades guide the flow throughout. In general, the motor efficiency is approximately 85 – 95%, and the hydraulic efficiency is approximately 80 – 90%. However, the hydraulic efficiency also depends on the pump profile type, which, in turn, depends on the required flow and head. Pump profiles are divided into three different types – radial, axial, and mixed-flow – depending on the direction that the flow leaves the impeller.

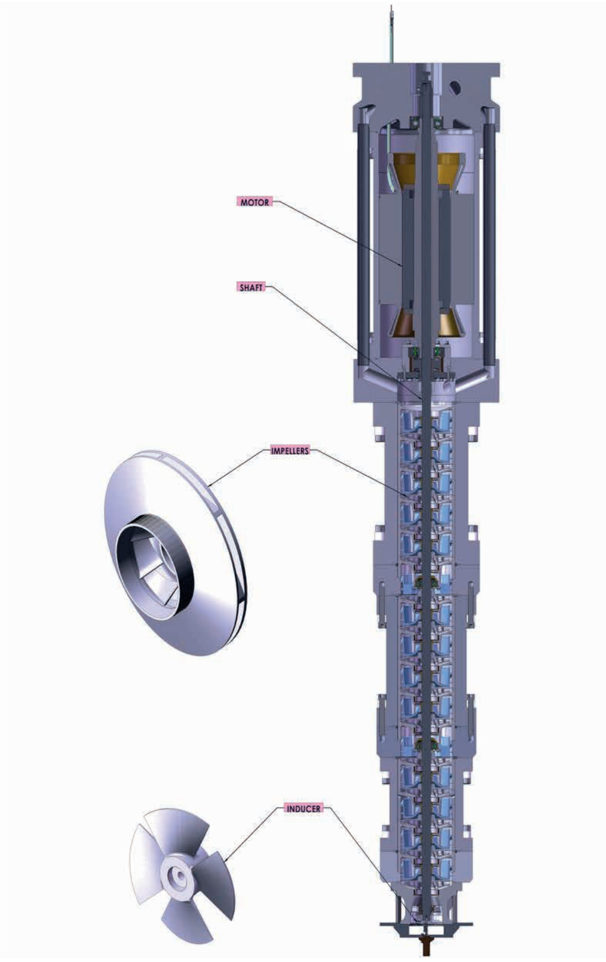

Figure 1. General structure of multi-stage cryogenic pump with submerged motor.

Table 1. Total head = head due to CE + head due to FT

Total head	CE head	FT head	Pump type	Efficiency
100%	80%	20%	Radial	80%
100%	70%	30%	Radial	84%
100%	60%	40%	Mixed	88%
100%	50%	50%	Mixed	90%
100%	40%	60%	Mixed	88%
100%	30%	70%	Mixed	84%
100%	0%	100%	Axial	80%

Radial-flow impellers, such as the one shown in Figure 1, deliver the flow perpendicular to the axis of rotation, and are utilised for relatively high-head, low-flow applications. In general, approximately 80% of the total head is produced by the centrifugal effect, while 20% is produced by flow-turning within the impeller channel. Rotation causes the flow to move radially out, while the blades cause the flow to turn within the impeller channel.

Axial-flow impellers, such as the inducer shown in Figure 1, deliver the flow along the axis of rotation, and are utilised for relatively low-head, high-flow applications. Nearly 100% of the head is produced via flow-turning along the blade surface, because the centrifugal effect is absent. In general, flow turning is not as effective as the natural centrifugal effect for producing head, because the flow has to continuously figure out the magnitude and direction of turning, as dictated by the blade profile.

Mixed-flow impellers, such as the one shown in Figure 2, deliver the flow in a direction that is neither axial nor radial. Instead, the flow is delivered at some slope, with the golden mean at 45° inclination being the preferred way out. Mixed-flow impellers offer a compromise where the two head-producing mechanisms are utilised and balanced, performing better than either axial or radial impellers.

Mixed-flow impellers are often considered more efficient than axial or radial impellers. However, the reasons are rarely provided. Usually, efficiency contours as a function of operating parameters are provided, revealing the superior performance of mixed-flow rotating turbomachines.

Elemental hydrodynamics

The rotating impeller produces head via the sum of two distinct mechanisms, driven by motor action and transmitted via the shaft. The first is due to the centrifugal effect (CE) because the liquid is forced to migrate radially outward, and its strength is measured by the increase in the wheel kinetic energy. The second is due to flow turning (FT) through the impeller channel because the curved (or cambered, usually circular-arc-shaped) blades force the flow to turn as it travels from the leading edge to the trailing edge, and its strength is measured by the reduction in the kinetic energy of the relative flow.

According to fluid dynamics theory, the overall hydraulic performance depends on the rates at which the flow is both centrifuged and turned within the rotating channel, and the preferred way for harvesting the two mechanisms is through a coordinated and balanced process, where the flow is continuously and simultaneously forced to turn (via the blades action), while being forced to migrate radially out (via the rotation action). Too much of either turning or centrifuging renders the process less effective.

Table 1 shows how the two mechanisms contribute to the total required head, and the associated hydraulic efficiency. It provides the split among the two head-producing mechanisms, and shows that the highest impeller efficiency is obtained when the two mechanisms contribute equally to the total head, or exactly 50% each.

The mixed-flow pump, using an impeller design with 50% CE head and 50% FT head, yields a 10-point efficiency advantage over the purely radial or the purely axial impeller designs. The fundamental reason for this is because the fluid prefers to experience pressurisation via an incremental process where the rate at which it turns is approximately equal to the rate at which it is being accelerated outward. Deviations from this golden mean split in either direction will degrade performance.

Test data of a significant number of production machines confirm the excellent performance of mixed-flow impellers, especially at or near the 50:50 split.

Quantitative example

The ideal velocity at which a fluid element travels within the impeller is SQRT (g x H), where g is the gravitational acceleration and H is the head. For simplicity, let the total head be H = 100 m and let the element be required to travel a distance L = 0.1 m. An associated frequency, which is equal to [SQRT (g x H)] / L, can be calculated for each contribution to the total head. Table 2 shows, for various CE head and FT head splits, the calculated frequency associated with each of the two mechanisms and the resulting frequency ratio = FR = CE-frequency / FT-frequency. Hydrodynamic-wise, a 30:70 split is equivalent to a 70:30 split because they both yield the same performance, but the frequency ratio (FR) for the latter would be below 1.0. At the two extremes (in theory only), 100:0 and 0:100 splits, the FR becomes infinity or zero, respectively.

This example breaks the manifestation of the two mechanisms into the most basic fundamentals. To produce lift (or pressure or head), each of the two mechanisms must be harvested at a certain frequency. Excellent performance is achieved when the two frequencies are equal. The highest performance is achieved when the FR is between 1/SQRT (2) = 0.707 and SQRT (2) = 1.414, with FR = 1 being the ideal. This range is equivalent to maintaining the split within the 1/3 – 2/3 (i.e. within 33:67 or 67:33) boundary. Too much domination by either mechanism will render the efficiency lower.

Emerging needs

With few cryogenic pump suppliers worldwide, competition is strong to satisfy emerging customer needs, such as enhanced product quality and reliability, full scale testing, on time delivery, new product development, variable speed operation, highly efficient hydraulics, and replacement of existing equipment at relatively low cost.

In order to meet increased industry needs, suppliers are forging ahead with increased product development. The design of compact high speed pumps is essential to the industry, and higher rotational speeds increase the need for mixed-flow type designs. In general, high speed pumps tend to be of the mixed-flow or axial types, both offering significant unit volume and weight reductions. Current pump operating speeds are generally below 8000 RPM, which is much lower than the reliability threshold for ball bearings.

In anticipation of emerging customer needs, NCI is focusing on improving its product line by utilising the following processes:

- Enhance product performance via R&D.
- Design validation via a state-of-the-art test facility, shown in Figure 3.
- Development of compact high speed pumps.
- Replacement of competitor pumps at low cost.
- Development of pump selector software.

NCI is developing pump selector software with approximately 100 production reference machines, some of which are of the mixed-flow type. The selector contains test data and hydraulic profiles for pumps tested at Nikkiso US and Japan and at Atlas Copco JC Carter, which Nikkiso recently acquired. The software quickly provides the proper solution, with accurate performance prediction, as well as ready-for-production geometric hydraulic profiles.

Conclusion

Mixed-flow pumps offer high performance due to effective cultivation of the centrifugal and flow turning effects along the liquid travel path. Peak performance occurs when the two head-producing mechanisms achieve a 50:50 distribution. Overall pump efficiency drops when deviating away from this golden mean in either direction.

Put a different way, mixed-flow pumps are efficient because the FR is near 1.0, which means that the liquid element experiences equal rates of lifting and spinning. Higher or lower FR, due to domination of either mechanism (CE or FT), yields lower efficiency. **LNG**

Table 2. Process frequency (Hz) and FR

CE Head	FT head	CE frequency	FT frequency	FR
50	50	221.5	221.5	1.00
60	40	242.6	198.1	1.22
70	30	262.0	171.6	1.53
80	20	280.1	140.1	2.00
90	10	297.1	99.0	3.00
99	1	311.6	31.3	9.96

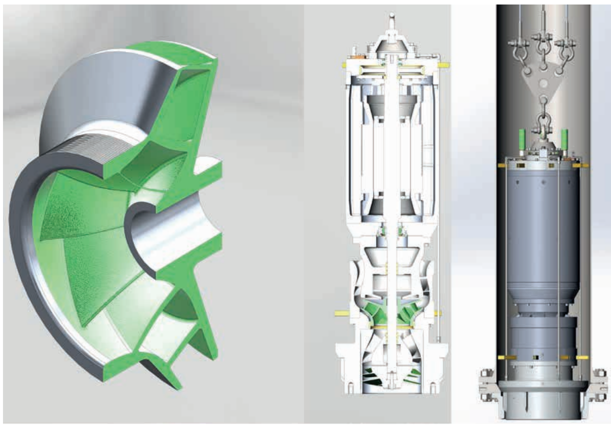

Figure 2. Nikkiso Cryo Inc. (NCI) single-stage mixed-flow pump (impeller on left hand side, in-column on right hand side).

Figure 3. NCI state-of-the-art test facility in Las Vegas, Nevada, US.