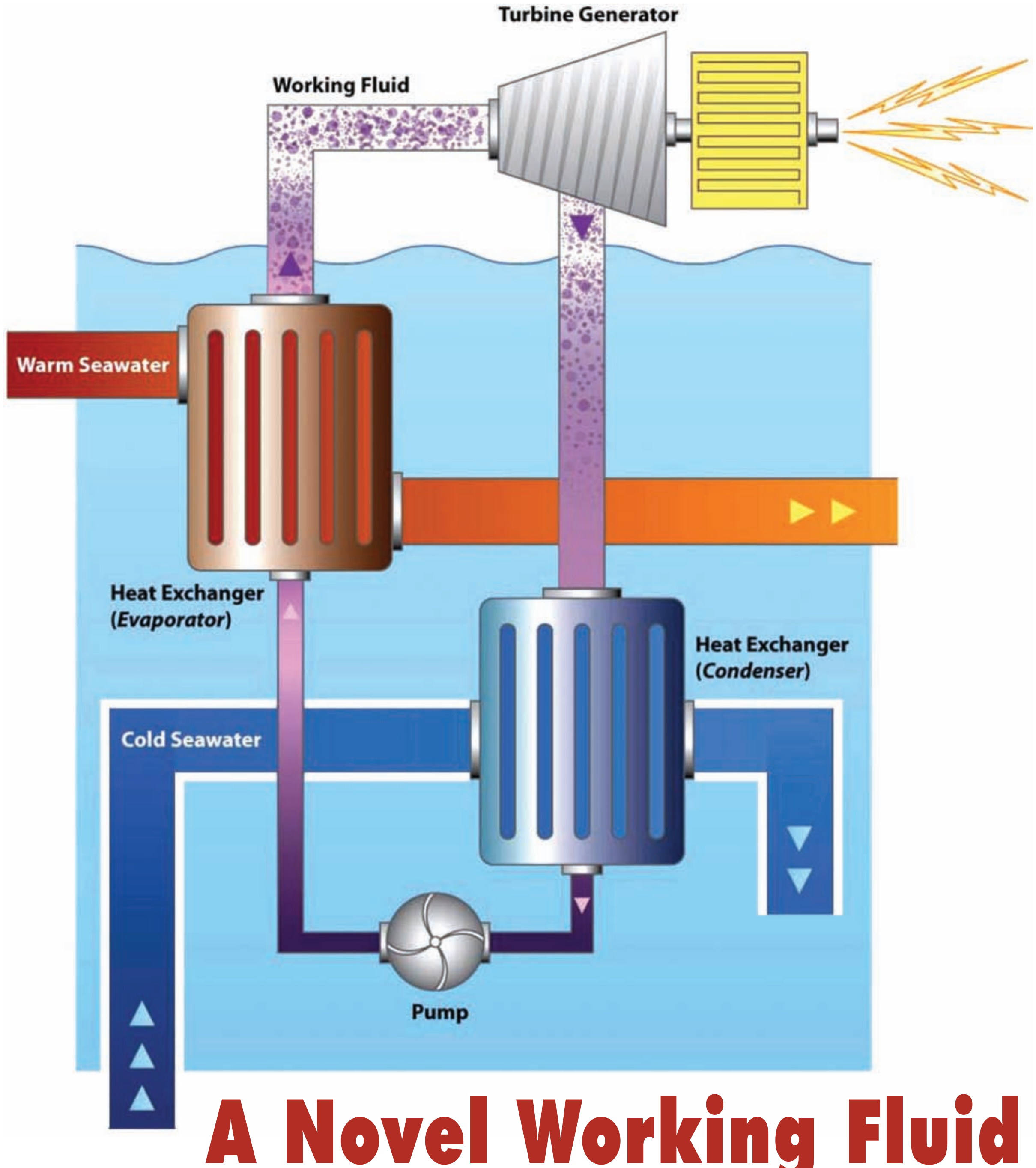

A Novel Working Fluid

for Ocean Thermal Energy Conversion

In this article, an azeotropic mixture of R-717/R-170 is proposed for ocean thermal energy conversion (OTEC) applications. R-717/R-170 is an environmentally safe working fluid mixture with no ozone depletion potential (ODP) and low greenhouse warming potential (GWP). This mixture can be used in OTEC power plants to replace conventional working fluids of medium vapour pressure. Due to the increase in pressure, a significant reduction in equipment size is anticipated, with consequent capital cost reduction.

Seventy one percent of the planet's surface is covered by oceans, and they absorb a staggering amount of energy from the sun each day. Jacques Cousteau has said that it is equivalent to the output from 16,000 nuclear power plants. Ocean thermal energy conversion (OTEC), or Hydrothermal Power Generation (HPG), taps into this energy to produce electricity.

Ocean thermal energy conversion relies on the fact that water near the surface is heated by sunlight whilst deep seawater is much colder. OTEC plants use warm surface water to heat ammonia or some other fluid that boils at a low temperature. The resultant gas is then used to drive turbines that produce electricity. The gas is condensed by cold water pumped up from the ocean depths and returned to the evaporator.

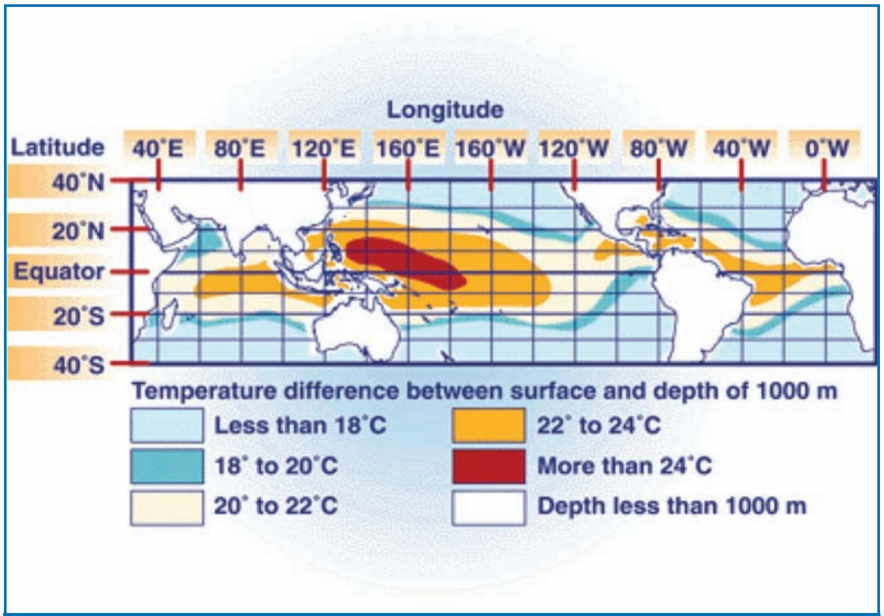

Fig. 1: Temperature differences between the surface and 1000m depth in the oceans

As can been seen from the diagram herein, the Indian Ocean contains one of the best OTEC resources located near populated areas. OTEC has a potential installed capacity of 180,000 MW in India. In 1998, India designed and built a one MW floating OTEC pilot plant 35km off coast off the coast of Tiruchendur, Tamil Nadu. Similar projects are planned for Andhra Pradesh. The Department of Ocean Engineering at the Indian Institute of Technology Chennai, has been researching OTEC since 1982. The US Navy is planning to build an 8 MW OTEC facility off the island of Diego Garcia in the Indian Ocean. The plant would also provide 1,250 gallons of drinking water to the base per day. The technology would be ideal for the Andaman & Nicobar Islands.

The OTEC concept was first conceived by D'Arsenoval in 1881. In 1979, a small OTEC pilot plant was installed in Hawaii which produced a net output of up to 18 kW. It used ammonia (R717) as the working fluid in a simple closed loop Rankine cycle. Since then, much research has been done to improve the performance of the closed loop OTEC plant, for example-

Anderson cycle

Developed in the 1960s by J. Hilbert Anderson of Sea Solar Power, Inc, heat is transferred in the evaporator from the warm sea water to the working fluid. The working fluid exits the evaporator as a gas near its dew point. The high-pressure, high-temperature gas is then expanded in the turbine to yield turbine work. The working fluid is slightly superheated at the turbine exit and the turbine typically has an efficiency of 90% based on reversible, adiabatic expansion. From the turbine exit, the working fluid enters the condenser where it rejects heat to the cold sea water. The condensate is then compressed to the highest pressure in the cycle, requiring condensate pump work. Thus, the Anderson closed cycle is a Rankine-type cycle similar to the conventional power plant steam cycle except that in the Anderson cycle the working fluid is never superheated more than a few degrees. The major parasitic energy requirements in the OTEC plant are the cold water pump work and the warm water pump work. This parasitic energy may be mitigated by using recently developed renewable energy devices such as ocean current turbines to compress

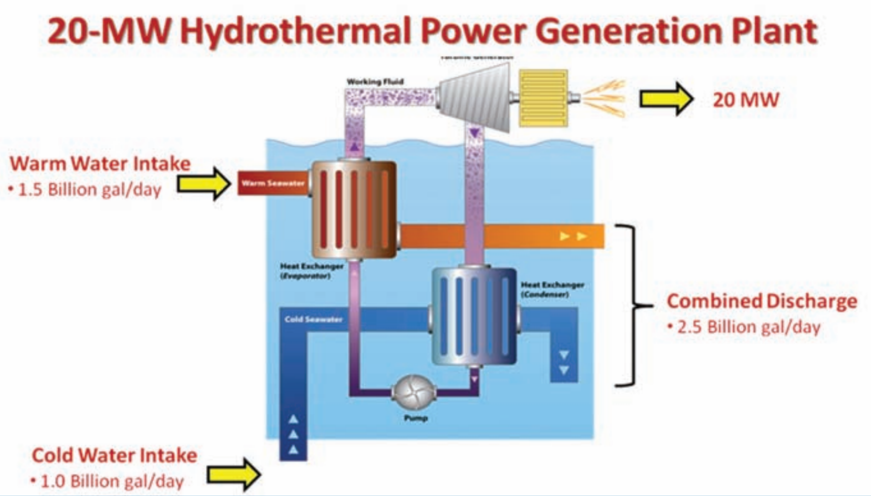

Fig. 2: 20MW OTEC schematic

air, thereby significantly increasing the efficiency of the system.

Despite continuing research, the barrier preventing commercial deployment of OTEC plants is the high initial capital cost. The closed loop OTEC plant basically comprises of a turbine and large marine heat exchangers as evaporator and condenser. In order to reduce the capital cost, these high cost components should be minimised and the best way to accomplish this objective is to use a higher vapour pressure working fluid providing higher heat flux density. The objective of this paper is to present a high pressure environmentally friendly working fluid with no ozone depletion potential (ODP) and low global warming potential (GWP) for OTEC applications.

OTEC-Strengths & opportunities: Clean and non-polluting Renewable energy resource.

Consistent: Can function 24 hours per day, 365 days per annum, unlike wind and solar energy which depend on fluctuating wind and sun.

Fresh Water Creation: 5 litres of fresh water for every 1000 litres of cold seawater can be created as a by-product.

Food: Farmed seafood products and temperate agriculture can be cultivated (or assisted for agriculture through cooling of roots of temperate plants in tropics) through the use of the discharge water.

Air Conditioning: The 5^0C cold seawater made available by an OTEC system creates an opportunity to provide large amounts of cooling to operations near the plant. The InterContinental Resort and Thalasso-Spa on the island of Bora Bora uses an OTEC system to air-condition its buildings.

OTEC – Weaknesses and threats: OTEC is uncompetitive in that fossil fuels produce cheaper electricity if the commercial cost of capital is taken into account - More research and development is needed to make OTEC cost efficient.

There may be difficulty in finding large enough demand for electricity in proximity to the areas of ocean which exhibits the largest temperature differences, although Florida, Puerto Rico, many Caribbean Islands and Hawaii are notable exceptions.

Transportation of energy and desalinated water may be unreliable, complicated and expensive, with the same exceptions as above.

Analysis: Development of a new working fluid

The use of ammonia as a working fluid offers significant benefits over other fluids, although it also possesses some less favourable characteristics, such as those associated with relatively high normal boiling point, high discharge temperature and oil miscibility. Therefore it would be desirable to develop an ammonia mixture that overcomes these disadvantages of pure ammonia. Research has identified one such mixture comprising ammonia (R-717) and ethane (R-170), which under certain compositions forms an azeotrope. This blend overcomes these drawbacks by significantly altering the fluid properties so that it can be more readily applied in higher pressure OTEC applications.

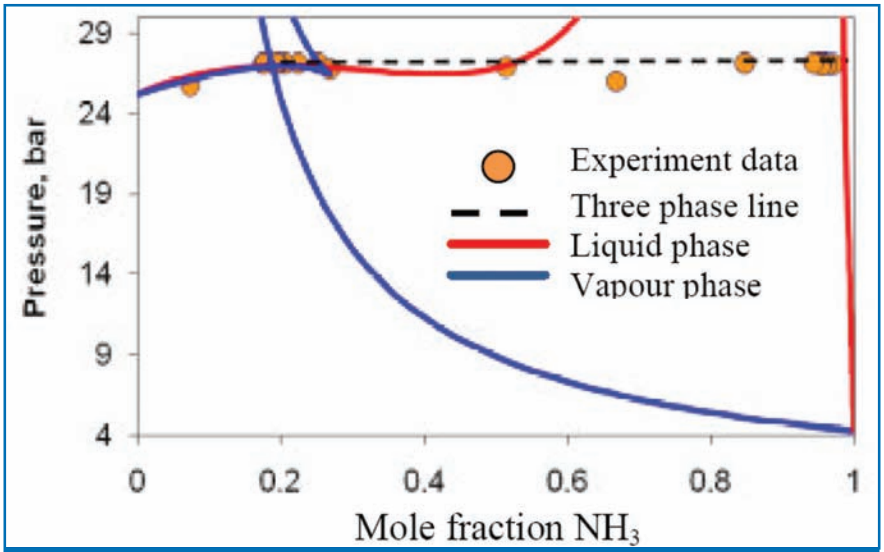

Fig. 3: Pressure – composition diagram of heteroazeotropic R-170/R-717 blend at 0^0C

Fig. 3 shows the temperature-composition diagram of the R-717/R-170 mixture. The R-717/R-170 mixture forms positive azeotropes up to the critical region. With an ideal binary mixture, the bubble and dew-point lines are separate for the entire range of compositions, and only converge when the composition reaches 100% or 0% of the components. However, for the R-717/R-170 blend the two lines converge at other compositions to form an azeotropic region. A positive azeotrope exhibits a rise in the pressure-composition curve at low temperatures. At these compositions, the mixture behaves as if it were a pure, single component fluid. As temperature increases, the azeotropic vapour composition moves from the zone of the liquid – liquid miscibility gap in the direction of higher mole fractions of ammonia. At the high temperature limit, the homogeneous positive azeotropy disappears. The three–phase line terminates in the liquid-liquid upper critical end point (UCEP), which lies approximately 10 K above the critical temperature for pure ethane (+44.9^{0}C). At low temperatures in the liquid-liquid-vapour three-phase range, the liquid phase is richer in ammonia. The R-170/R-717 blend also forms heterogeneous positive azeotropes (where the two components are not homogeneously mixed) up to the liquid-liquid UCEP where the occurrence of three fluid phases is observed as a liquid, vapour, and liquid sequence which is contrary to conventional three-phase equilibria with liquid-liquid-vapour sequence.

Discussion

In an OTEC plant, the temperature of the surface water ranges from 22 to 30^{0}C and deep sea water from 4 to 5^{0}C, giving a temperature differential of 17 to 26^{0}C. For this application, the organic Rankine cycle (ORC) is usually employed because of its excellent performance in converting low grade heat into electricity. The performance of the ORC is directly related to the thermodynamic properties of the working fluid. Consequently, a good working fluid could generate more efficient and lower cost plants. To date, ammonia (R717), propane (R290), propylene (R1270), 1,1,1,2-Tetrafluoroethane (R134a) and 2,3,3,3-Tetrafluoropropene (R1234yf) have been proposed as working fluids in the ORC for OTEC applications. These are all medium vapour pressure fluids exhibiting similar vapour pressure.

Fluid	Efficiency (%)	Pevap (kPa)	Pcond (kPa)
R717	4.67	1099	554
R290	4.49	1027	584
R1270	4.48	1245	718
R717/R170(55/45)	4.34	2208	1285

Table 1: Thermodynamic cycle calculation results for OTEC application

Table 1 lists the theoretical efficiency of the ORC calculated under the typical evaporation and condensation temperatures of 28 and 7^{0}C for OTEC applications. The theoretical efficiencies of the conventional fluids are very similar. The efficiency of R717/R170 (55/45) mixture is some 5% lower than the average value of the others. The biggest advantage of R717/R170 (55/45) mixture, however, lies in the higher vapour pressure resulting in a significant reduction in turbine and heat exchanger sizes. The power plant size is dependent upon the vapour pressure of the working fluid. With increasing vapour pressure, the size of the turbine and heat exchangers decreases while the wall thickness of the pipe and heat exchangers increase. Due to the increase in pressure, a 50% reduction in the size of components is expected with the use of this mixture compared to the other fluids. This, in turn, would lead to a significant reduction in capital cost. Rather than half the dimensions for a fixed power output, my approach would be to design the largest turbine set that can be built inside an ISO standard 40 foot shipping container and then maximise the power output using an optimised R717 / R170 blend.

Modular ORC design using ISO standard 40 foot shipping containers.

The above depicts a modular ORC system using ISO standard 40 foot shipping containers. The modular design lends itself to scalability and cost effective manufacturing.

Using propane (R-290) as the working fluid, the theoretical electrical output is 9.65 MWe which can service a large size data centre. However, when using R717/R170 (55/45), the theoretical electrical output increases to 20.23 MWe. So we have more than doubled the power output with no increase in equipment size and negligible increase in equipment cost.

Condition		Normal Operation - No solar Boost
Deep seawater source temperature (entry)	^{0}C	4.5
Condenser Heat Exchanger waterside temperature difference	^{0}C	1.5
Saturated WF Condensing Temperature	^{0}C	6
Condenser Subcooling	^{0}C	2
Surface Seawater Entry Temperature	^{0}C	24.5
Evaporator Heat Exchanger waterside temperature difference	^{0}C	1.5
Turbine WF Inlet Saturation temp	^{0}C	21.5
Turbine Inlet WF superheat	^{0}C	1

Table 2: Hydrothermal Turbine Design Conditions

The pressure increases can be easily managed. At present, the condensing pressure of R410A in a typical air-conditioner during summer is about 2700 kPa while the evaporator pressure of R717/R170 (55/45) mixture in a typical OTEC plant during summer is about 2200 kPa.

For this chosen composition, the following generalisations can be made about its characteristics when used in OTEC applications:

The mixture exhibits complex phase behaviour, but it is azeotropic throughout the operating range, thus avoiding complications associated with temperature glide.

The NBP is significantly lower than pure R-717 and most other conventional working fluids, thus avoiding problems associated with air and moisture ingress.

Volumetric refrigerating effect (VRE) exhibits a synergetic behaviour and gives considerably higher values of VRE than the pure components, thus requiring a turbine with smaller swept volume.

Discharge temperature is dramatically lower than R-717, which favours system reliability, and also permits the use of single-stage turbines with large temperature lifts.

Name	ECP717
Composition (molar)	45% R170, 55% R717
Molar Mass	22.9
NBP (°C)	- 52.5
Critical temp (°C)	41.9
Freezing temp (°C)	-97
ATEL (ppm)	550 – 570
LFL (% vol)	4.0 – 4.2
Likely safety class	B3
ODP	0
GWP (100)	~2

Table 3: Characteristics of new blend

An improved heat transfer, particularly in the evaporator, was observed, resulting in higher evaporating temperatures, which equates to an incremental improvement in cycle efficiency; and the rate of degradation in system efficiency and capacity as the heat rejection (or heat sink) temperature rises for the mixture is less than the rate of degradation of ammonia. It has good miscibility with mineral oils; thereby negating problems associated with highly hygroscopic Polyalkylene Glycol (PAG) oils and avoids the necessity to use the new high-cost hydro-treated lubricants.

Conclusions

A novel azeotropic mixture of R717/R170 is proposed for OTEC power plants to replace conventional working fluids. R717/R170 is an environmentally friendly working fluid with no ozone depletion potential and low greenhouse warming potential. It has a saturation pressure greater than R717, higher refrigerating capacity, lower compression ratio, and reduced turbine discharge temperature. It is considered to be particularly applicable for OTEC applications. Due to the increase in pressure, a significant reduction in the size of equipment is expected, which in turn will result in an initial cost reduction. ■

Nicholas Cox, Managing Director, Earthcare Products Ltd, is considered a leading authority on environmentally friendly refrigeration & airconditioning and presented many papers. A fellow of the Institute of Sales and Marketing Management, he was awarded a graduateship of the City and Guilds of London Institute for his work on how industry could better utilise natural refrigerants and energy efficiency. He has advised both the UK government and EU commission on environmental aspects of refrigeration and AC, and carried out reviews and submitted written responses to proposed and pending policy documents and legislation regarding refrigerant issues.