Working Fluid Candidates Selection for 100kW Ocean Thermal Power Generation Based on Environmental, Safety, and Thermodynamic Constrains

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Abstract – Due to its equatorial location, Indonesia has a huge amount of ocean thermal energy resource. However, this alternative renewable energy resource is still not well developed yet. In this paper, a selection procedure of working fluid for a 100 kW ocean thermal power generation is presented. The screening process was based on environmental, safety and thermodynamic constrains to obtain the best working fluid for this application. Five working fluid candidates are analyzed i.e. ammonia, butane, butene, isobutane, and isobutene. In term of environmental and safety aspects, ammonia is the best solution. But in thermodynamic point of view, isobutane shows the highest power conversion efficiency of 6.13%, whereas ammonia's efficiency is only 1.87% for the same power output.

Keywords: OTEC, working fluid, ODP, GWP, GSF, efficiency.

1. Introduction

As one of archipelago countries, Indonesia has 17,504 islands; around 10,000 of them can be categorized as small islands; which made it as the second longest coastline in the world [1]. The existence of these small islands, some of them are unfortunately isolated, is a challenging issue to deal with in term of how to provide the electricity power supply for them. Although the current national electricity ratio is 98%, there are some areas with less 90% or even less than 70% [2].

1.1. Power Generations in Indonesia

Nowadays, the majority of Indonesia's power generations are dominated by fossil-fueled power plants [2]. In the fact, Indonesia has large and very diverse renewable energy resources which are still not optimally developed as tabulated in Table 1 [3]. The renewable energy utilizations are currently focused on geothermal, hydro, biomass, solar and wind energy. But, their utilizations are relatively smaller than their existed potentials. Moreover, Table 1 also shows the other renewable energy alternatives which are not explored yet "the blue ocean energy" such as wave energy, tide and tidal energy, and ocean thermal energy. Total ocean renewable energy resources are 63,801 MW which 7.52% of them are contributed by the tide and tidal energy ones. The previous research reported that the tidal energy, especially the current one, in the narrow straits is considerably much higher in archipelagos, such as in the Nusa Tenggara and Maluku Islands including Bali Strait [4]. Another prospective renewable ocean energy is the ocean

thermal energy which has resources of 41,012 MW. This valuable energy is much higher than biomass resources and almost half of hydro resources in Indonesia. Based on this fact, this energy should be considered as one of alternative candidates for providing electrical power supply in Indonesia.

Figure 1 illustrates potential locations for ocean thermal power plant or ocean thermal energy conversion (OTEC) in Indonesia [5]. Moreover, Mentawai Islands Regency with its chain of around seventy islands in West Sumatera Province is another prospective site for OTEC [6, 7].

In this paper, an investigation of prospective working fluid candidates for OTEC is presented. The working fluid selection is one of important steps to obtain the most appropriate working fluid for gaining the best OTEC system in term of technical and nontechnical aspects. The determination of the best potential working fluid is not only based on the environmental and safety consideration. Considering the inherent low efficiency issue of OTEC-based power generation, an analytic thermodynamics-based analysis is also performed to obtain the best system efficiency.

Table 1. Renewable energy resources in Indonesia [3].

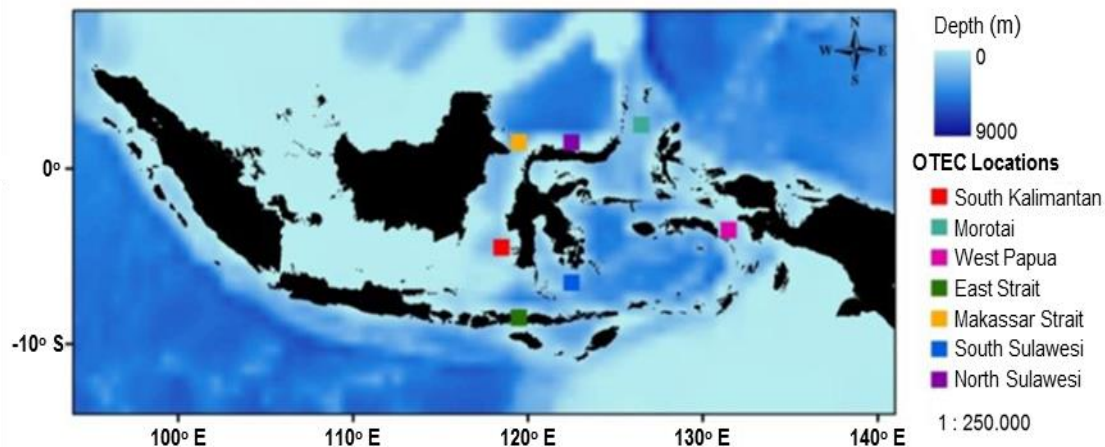| Energy Type	Resources	Potential	Installed Capacity
Geothermal		29,544 MW	1,948.3 MW
Hydro	75,091 MW	45,379 MW	4,431.59 MW
Mini-micro hydro		19,385 MW	267.79 MW
Biomass	35,654 MWe		142.02 MW (*off grid*)
Solar energy	4.80 kWh/m^2/hari		24.42 MW
Wind energy		970 MW	143.03 MW
Wave energy	17,989 MW		
OTEC (Ocean Thermal Energy Conversion)	41,012 MW		
Tide and tidal power	4,800 MW		

Figure 1. Map of bathymetry Indonesian seas for OTEC sites [5].

1.2. Principle of Ocean Thermal Power Generation

The basic principle of an ocean thermal power generation or OTEC is based on the natural characteristic of seawater which has a thermal difference between seabed and surface one. The surface seawater's temperature is quite warmer than the seabed's one as illustrated in Figure 2 [8], [9]. This phenomenon is dominantly influenced by the solar radiation. In this paper, the area of Indonesia territorial waters in 125°E 30° N – 127.5° E 5° N are selected as the location candidate for OTEC. In this region, the surface and deep layer (1,000 m) seawater temperatures are in the range of 28.44 – 31.23°C and 4 – 5°C, respectively [10].

By adopting the natural characteristic of ocean water, a basic scheme of OTEC is described in Figure 3. The surface water which has warmer temperature is used to evaporate a low boiling temperature working fluid for generating steam. Then, the steam is guided to rotate a steam turbine which direct coupled with a generator. From the steam turbine, the working fluid is re-converted to the fluid form. This conversion is performed in a condenser which uses the colder temperature seawater as a heat extraction media from the working fluid. In this liquid form, the working fluid is easily back pumped to the evaporator for making a complete Rankine power cycle.
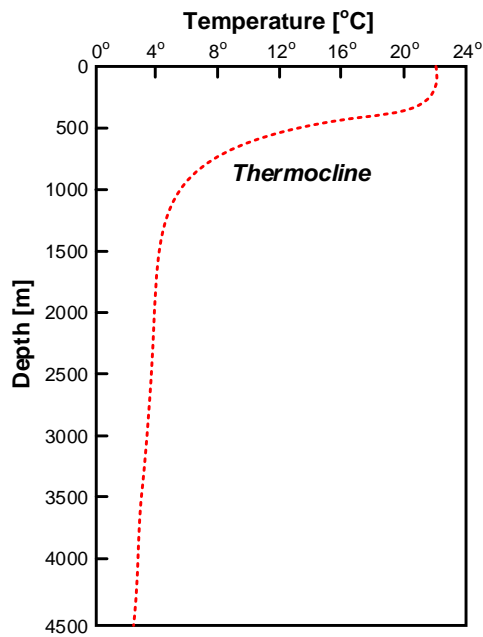

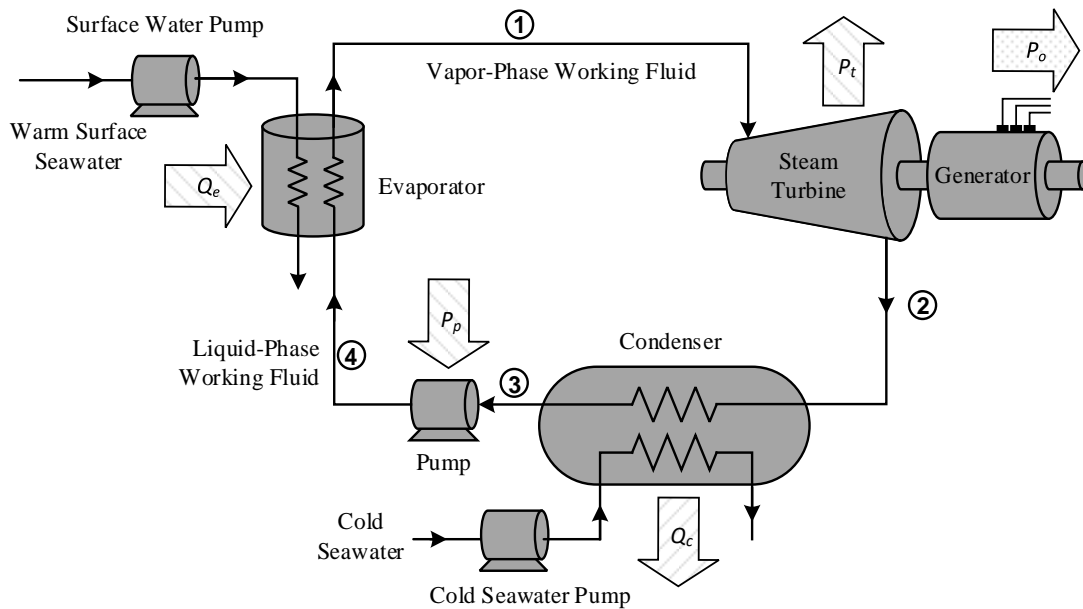Figure 2. Typical thermocline ocean water characteristic [8], [9].

Figure 3. Basic principle of Ocean Thermal Power Generation or OTEC

2. Research Method

There are several criteria have to be considered for working fluid candidates selection. They must cover some important aspects such as environmental sustainability, ozone depletion potential (ODP), global warning potential (GWP), safety (non-flammable, non-toxic and non-corrosive) as well as some critical thermodynamic constrains [11].

Due to the quite narrow temperature difference range in OTEC power cycle, the first requirement is that the working fluid should have a low boiling temperature. Considering this factor, water is quite not applicable for OTEC power cycle. As tabulated in Table 2, the normal boiling temperature of water is 99.97°C. This temperature is much higher than the annual average temperature of surface seawater. Table 2 also shows other working fluids which more suitable for OTEC application i.e. ammonia, butane, butene, isobutane, and isobutene. The temperature and pressure of these working fluids' critical point are much lower than water as well as their normal boiling temperature. Thus, these five working fluids will be more detail analyzed in term of power cycle thermal efficiency.

Table 2. Thermodynamic properties of working fluid candidates [12]

Working Fluid	Critical Point			Normal Boiling (°C)
	Temperature (°C)	Pressure MPa)	Density (kg/m^3)	
Water (H_2O)	373.95	22.064	322.0	99.97
Ammonia (NH_3)	132.25	11.333	225	-33.33
Butane (CH_3-2(CH_2)-CH_3)	151.98	3.796	228	-0.49
Butene (CH_3-CH_2-CH=CH_2)	146.14	4.005	237.89	-6.31
Isobutane ($CH(CH_3)_3$)	134.66	3.629	225.5	-11.75
Isobutene (CH_2=$C(CH_3)_2$)	144.94	4.010	233.96	-7.0

Moreover, the ODP and GWP values of the working fluid candidates must be low and less 150, respectively [13]. Based on NFPA 704 standard, the global safety factor (GSF) can be easily determined by using a set of criteria i.e. health (H), instability (I) and flammability (F) activities of the working fluid as formulated in Eq. (1) as follows [11]

$$GSF = (\alpha \times H) + (\beta \times I) + (\gamma \times F), \tag{1}$$

where α, β, and γ are weightage factor for each safety criterion. These weightage factors are adopted to give different weight for the working fluid hazard. The most concern is given to the flammability aspect (γ = 45%) due to its possible risk of auto-ignition hazard in the case of leakage. For the similar reason, the instability factor should be given more attention by adopting β = 35%. Lastly, the health hazard's weightage factor is α = 20%. NFPA 704 stated each safety's value in the range between 0 and 4 [15]. The GSF should be less than 2.5. Table 3 shows safety factors of the selected working fluid candidates. Except isobutene which normally stable but can become unstable at elevated temperatures and pressure, all working fluid candidates is quite safe and may be adopted for OTEC. However, the isobutane will be covered in the computational analysis to investigate in term of thermodynamic point of view.

Table 3. Safety factor of working fluid candidates

Working Fluid	ODP	GWP	H	F	I	GSF
Ammonia	0	0	3	1	0	1.05
Butane	0	7 [16]	1	4	0	2.00
Butene	0	3 [17]	1	4	0	2.00
Isobutane	0	5 [18]	0	4	0	1.80
Isobutene	0	-	2	4	1	**2.55**

3. Results and Discussion

As illustrated in Figure 3, an OTEC power cycle is basically a Rankine power cycle. The input thermal power can be calculated as follows [8], [9]

$$Q_e = \dot{m}_{sw} c_{pe}(T_{sw-i} - T_{sw-o}), \tag{2}$$

where Q_e is the evaporator thermal power, $\dot{m}_{sw}$ is the mass flow rate of surface seawater, c_{pe} is the heat transfer constant between surface seawater and working fluid, T_{sw-i} and T_{sw-o} are the surface seawater temperature on the inlet and outlet sides, respectively. By using the similar calculation, the condenser can be formulated as follows

$$Q_c = \dot{m}_{cw} c_{pc}(T_{cw-o} - T_{cw-i}), \tag{3}$$

where Q_c is the condenser thermal dissipation, $\dot{m}_{cw}$ is the mass flow rate of cold seawater, c_{pc} is the heat transfer constant between cold seawater and working fluid, T_{cw-i} and T_{cw-o} are the cold seawater temperature on the inlet and outlet sides, respectively.

To check the performance of all working fluid candidates, the EBSILON®Profesional software is adopted to perform various computation analyses. The scheme of power generation system is illustrated in Figure 3. For the analysis, the output power is kept constant at 100 kW. For providing a more reasonable comparison, the mass flow rate of working fluid is also maintained at around 4 kg/s for all working fluid. The temperatures of surface and cold water are set to be 29°C and 4°C, respectively. The generator efficiency is assumed as 96% with the isentropic efficiency of turbine and pump of 88% and 80%, respectively. Then, the calculated variables are the injected heat from surface seawater, absorbed heat by cold seawater, and also working fluid thermodynamic properties at each state. Then, the system efficiency can be easily calculated by using following formula

$$\eta = \frac{P_{output}}{P_{input}} \times 100\% . \tag{4}$$

Table 4 summarizes the computational analysis results. As shown in Table 4, except ammonia, the transferred heat in the evaporator and the condenser are quite similar among the working fluid candidates. For the same power output, ammonia requires the highest amount of heat to convert it from liquid phase to vapor one. Even though the pump's power (1.058 kW) is the smallest one, this requirement makes its efficiency much smaller than the other working fluid candidates. The contrasted result is shown for isobutane working fluid. The isobutane's efficiency (6.13%) is the highest one among the others by drawing the highest pumping power of 1.892 kW. Thus, considering the efficiency constrain, isobutane can be considered as the most appropriate working fluid for OTEC application. For isobutene, although it was quite out of the safety criteria range, this working fluid shows a good performance in term of the power conversion efficiency. This working fluid selection mechanism might be applied to any other power generations with different power capacities.

Moreover, for providing more complete cycle process illustration, the *T-s* diagrams of all working fluid are figured in Figure 4 – 8. The important thermodynamic properties of each state are tabulated in Table 4. Except ammonia, all working fluid candidates are categorized as dry fluid type as illustrated in Figure 5 – 8. A dry fluid type has a *T-s* diagram with *ds/T* > 0 as depicted in the shape of *T-s* diagram. The different *T-s* diagram is shown in ammonia's one. Ammonia is classified as wet fluid which has *ds/T* < 0 characteristic as presented in Figure 4. Also, as shown in Figure 4 – 8, due to the tight narrow temperature difference margin in OTEC, the loci of state 3 and 4 are looked in the same spot. Even thought, they are actually in the different position as zoomed in in the inserted view.

Table 4. Computational analysis results

|	Parameter	Ammonia	Butane	Butene	Isobutane	Isobutene
State 1	T_1 (ºC)	28	28	28	28	28
	P_1 (bar)	6.40	2.66	3.25	3.80	3.3
	h_1 (kJ/kg)	1662.233	625.254	434.132	592.013	436.560
	s_1 (kJ/kgK)	6.109	2.422	1.456	2.312	1.466
State 2	T_2 (ºC)	16.281	9.164	7.333	9.370	7.674
	P_2 (bar)	5.200	1.250	1.600	1.875	1.600
	h_2 (kJ/kg)	1637.766	599.348	409.345	568.269	411.238
	s_2 (kJ/kgK)	6.121	2.435	1.468	2.323	1.479
State 3	T_3 (ºC)	5.229	5.166	6.036	5.123	5.282
	P_3 (bar)	5.200	1.250	1.600	1.875	1.600
	h_3 (kJ/kg)	367.427	212.025	27.099	211.788	27.698
	s_3 (kJ/kgK)	1.559	1.043	0.099	1.043	0.101
State 4	T_4 (ºC)	5.266	5.246	6.136	5.244	5.381
	P_4 (bar)	6.450	2.710	3.300	3.850	3.350
	h_4 (kJ/kg)	367.674	212.332	27.447	212.217	28.055
	s_4 (kJ/kgK)	1.559	1.044	0.099	1.043	0.102
m (kg/s)		4.266	4.233	4.211	4.396	4.122
P_t (kW)		104.167	104.167	104.167	104.167	104.167
Q_e (kW)		5522.677	1747.713	1712.538	1669.569	1683.870
Q_c (kW)		5419.357	1639.362	1609.626	1567.081	1580.967
$P_{p\text{-}shaft}$ (kW)		1.058	1.366	1.467	1.892	1.475
P_o (kW)		100	100	100	100	100
Efficiency (%)		1.87	5.88	6.00	6.13	6.10
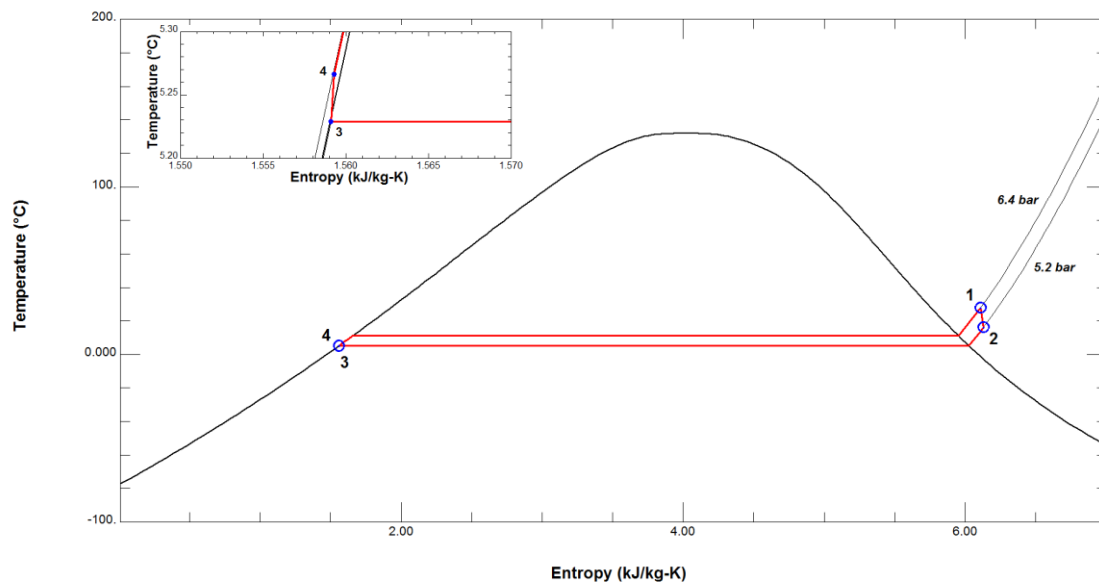
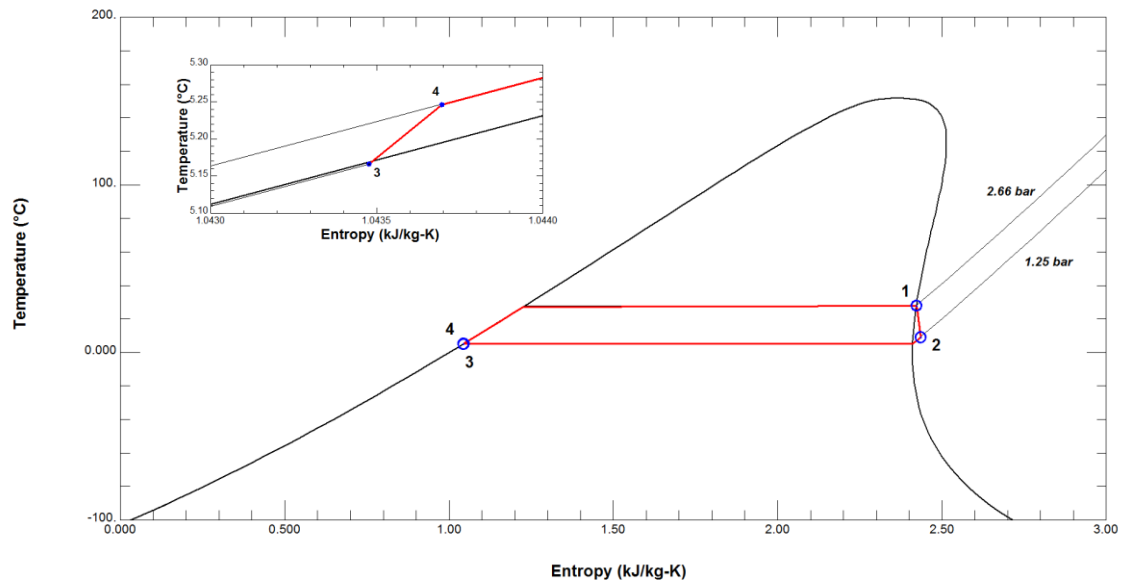Figure 4. *T-s* diagram of ammonia working fluid

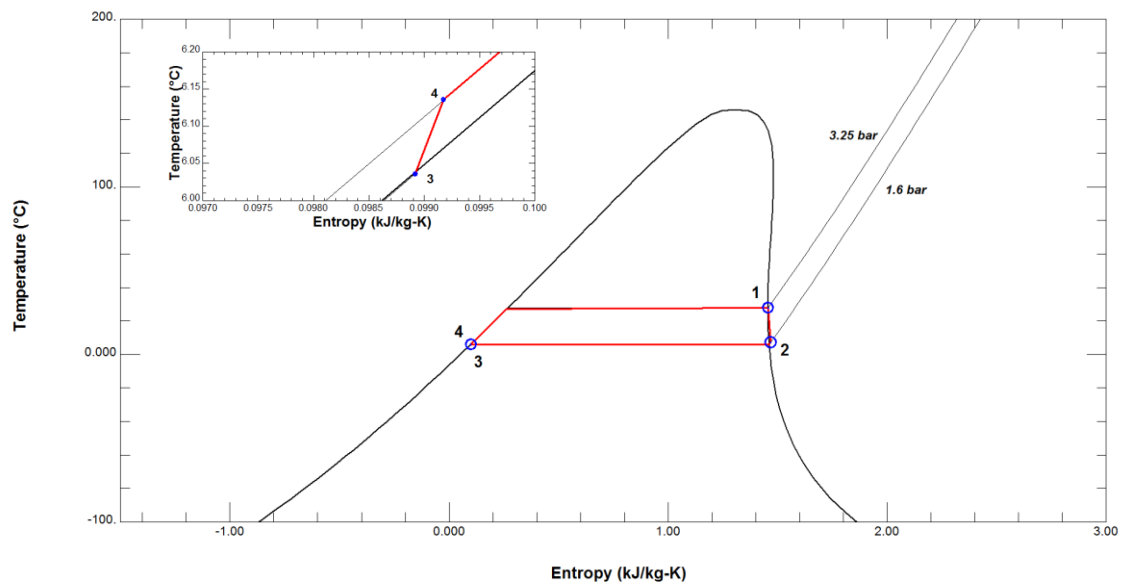Figure 5. *T-s* diagram of butane working fluid

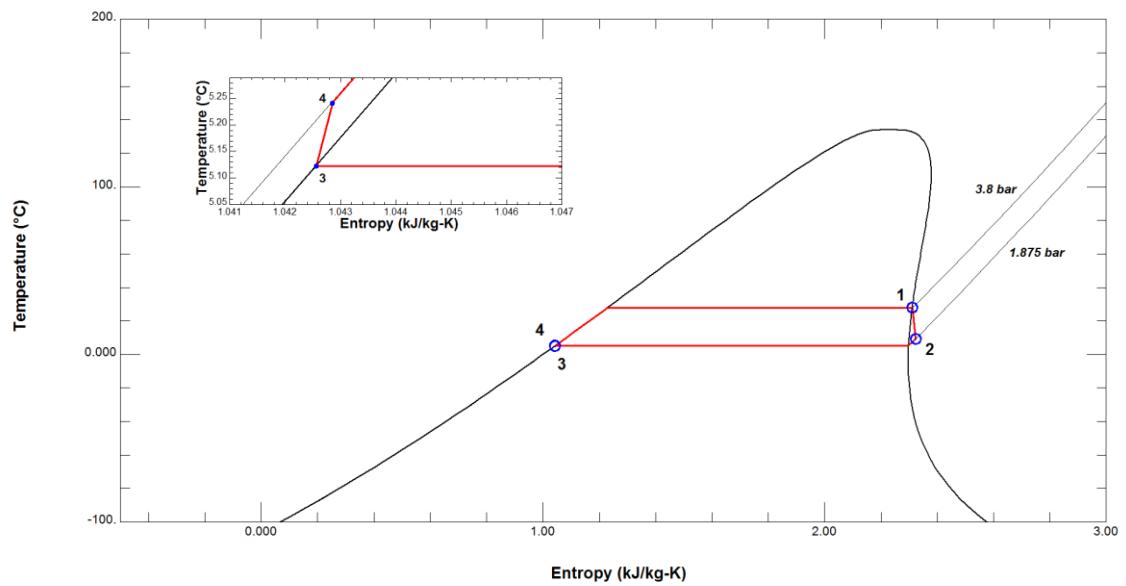Figure 6. *T-s* diagram of butene working fluid

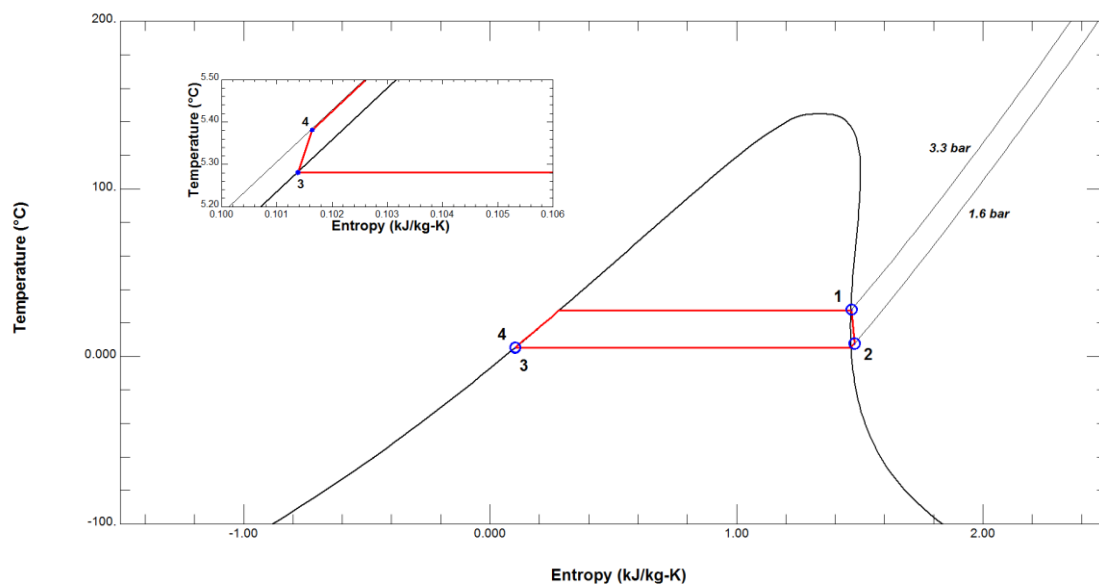Figure 7. *T-s* diagram of isobutane working fluid

Figure 8. *T-s* diagram of isobutene working fluid

4. Conclusions

In this paper, a selection procedure of working fluid for a 100 kW ocean thermal power generation was presented. The screening process was based on environmental, safety and thermodynamic constrains to obtain the best working fluid for this application. Five working fluid candidates were analyzed i.e. ammonia, butane, butene, isobutane, and isobutene. In term of environmental and safety aspects, ammonia is the best solution. But in thermodynamic point of view, isobutane demonstrated the highest power conversion efficiency of 6.13%, whereas ammonia's efficiency is only 1.87% for the same power output.

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