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Energy return on energy invested for the production of methane from hydrates by electrical heating and by hot water injection

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Abstract: In this paper we expand our previous publications on the energy balance (EROI) in the production of methane from methane hydrate (MH) submarine reservoirs via electrical heating and by hot water injection. In the case of hot water injection the heat transfer problem with phase change was initially solved by a standard finite difference scheme in cylindrical coordinates. This scheme proved to be unstable in the region inside the pipe located at the center of the reservoir. In order to avoid this numerical instability our previous solution assumed a linear temperature dependence for the temperature along the heating pipe. In this paper we avoid the previous approximation for the heating of MH. We obtain stable heat transfer solutions by transforming the initial finite difference scheme using the Gauss theorem. The transformed discretized system is stable. The results indicate that for a 500 meter long reservoir (with a radius of 100 meters), the flow of water in a 1 meter diameter pipe located at the center of the reservoir (initial temperature of 200 C and end temperature of 2 C) will melt the hydrates with an EROI (energy out/energy in) of the order of 30 at the beginning of the operation, and of the order of 7 after 30 years of operation.

1. Introduction

In view of the large energy reserves associated with methane hydrate deposits in the word, we decided to evaluate the energy balance (energy out / energy in) associated to the possible production of methane from submarine hydrate deposits. Should this partial energy balance turn out to be less than unity, the complete EROI (Energy Return On energy Invested) would be even less than unity when the energy required for the construction, maintenance (and decommissioning) of the system is added. No additional calculation would then be required. The concept of EROI is shown in Figure 1. Figure 2 illustrates the concept of a partial EROI less than unity, where the balance of energy only considers applied energy.

In previous papers [1-2] we calculated the primary energy balance (energy out / applied energy) for the possible production of methane from submarine deposits by low frequency (60Hz) electrical energy. We examined different heater locations and different heater lengths, and found that for the optimal heater positions and lengths the EROI was 1.66 (5/3). Figure 3 shows some of the results for the EROI obtained for different heater powers.

Figure 1. The concept of EROI when all the required energy is less than the energy produced in a given process.
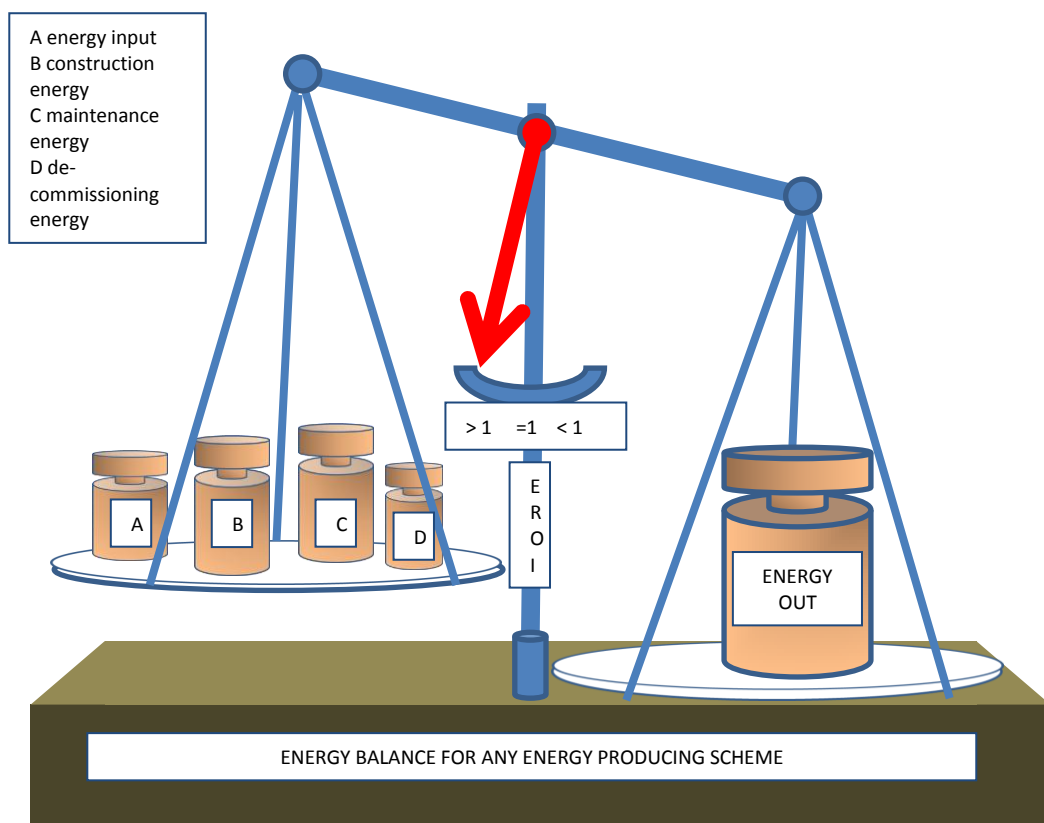
Figure 2.. The concept of partial EROI when only the applied energy in a given process is compared with the smaller produced energy.
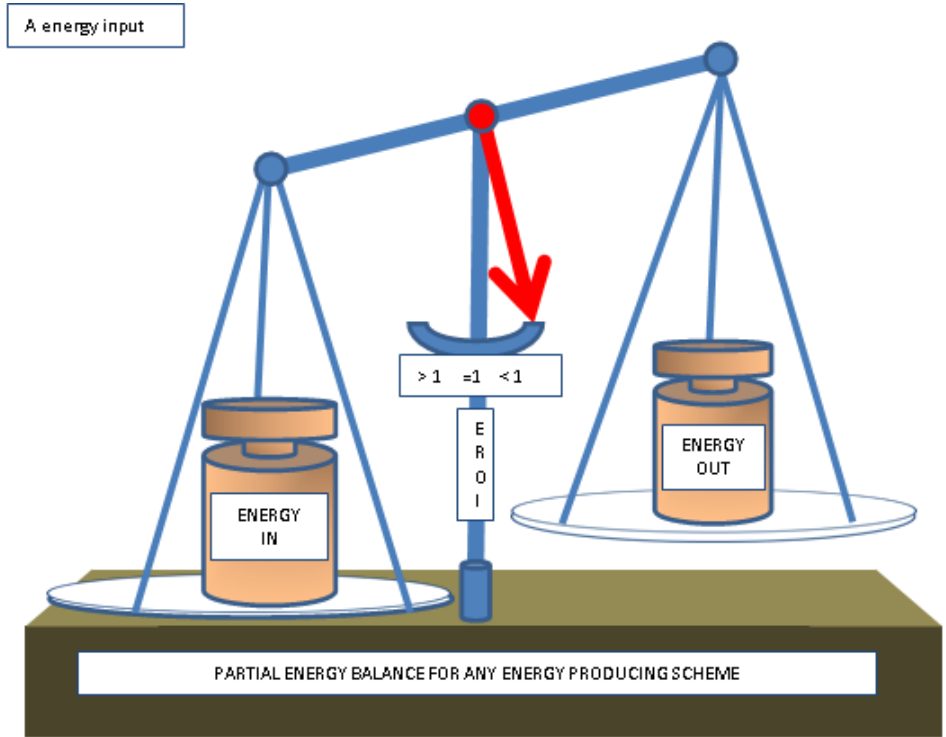

Figure 3. Energy gain (Energy out/Energy in) over a 5 year period vs heater length for different electrical (60 Hz) heater powers. The heaters are located at the top of the reservoir (radius=0.1524 m, Tmax=200 C). The reservoir is initially at 2C, and the melting temperature used was 20 C. Only energy gains above the dotted line will yield a positive energy gain for 50-60 Hz electrical heating. This is so because the applied electrical energy is produced by conventional thermal plants with efficiency of the order of 33-34%.
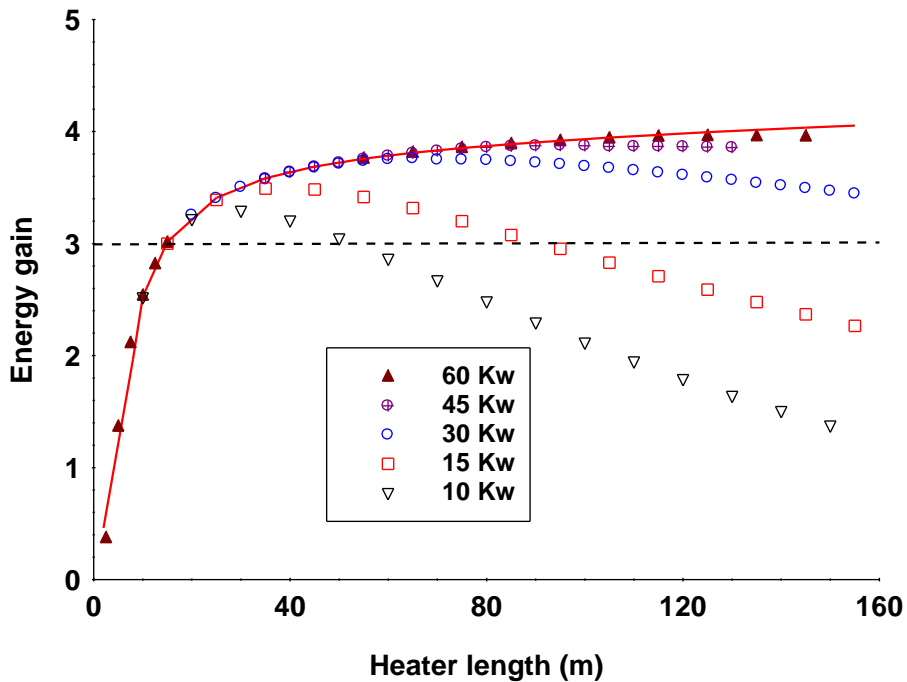
We next considered [3] the methane production via hot water injection – the scheme suggested in Japan for production in the Nankay trough [4]. We considered a methane hydrate reservoir 500 meters long with a radius of 100 meters at an initial temperature of 2 C. A pipe located at the center of the reservoir carries the hot water output of a floating cogeneration plant. The configuration of the system considered in our model is shown on Figure 4.

Figure 4. The system considered: Methane hydrate reservoir: length=500m, radius=100m.Pipe: length=500 m, diameter=1m, water enters at 200 C and exits at 2 C Water velocity=1m/sec
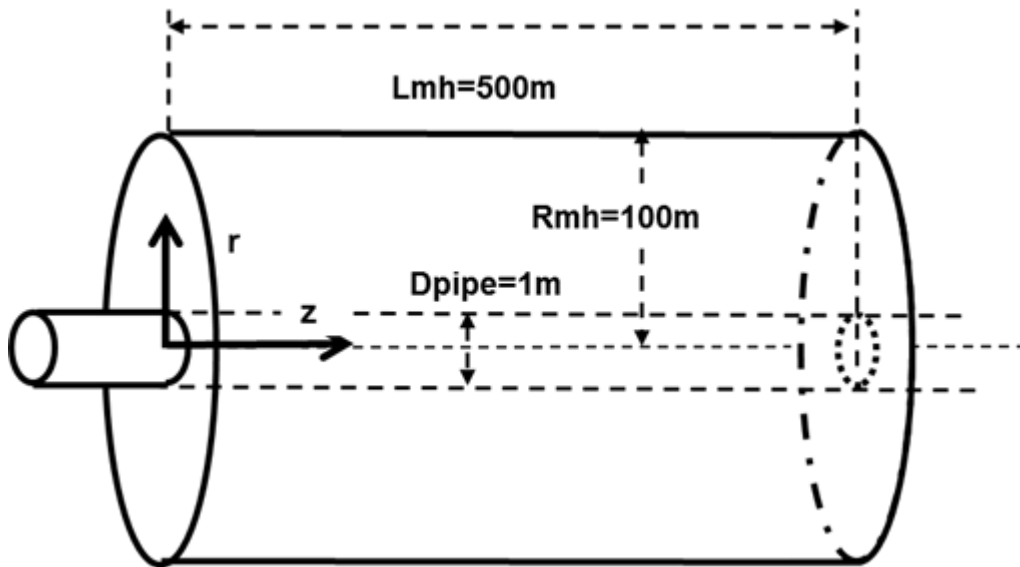
In order to solve this problem we first modeled the heating via a standard second order finite difference heat transfer scheme in cylindrical coordinates. The region inside the pipe considered heat conduction and convection processes, while the solution inside the reservoir considered heat conduction and change of phase according to the enthalpy method [1]. The heat transfer equations that define the temperatures in the well $T_w(r,z)$, and in the reservoir $T(r,z)$, are shown below. In the well:

$$\frac{\partial^2 T_w(r,z)}{\partial r^2} + \frac{1}{r}\frac{\partial T_w(r,z)}{\partial r} + \frac{\partial^2 T_w(r,z)}{\partial z^2} - \frac{v(r)}{\kappa_w}\frac{\partial T_w(r,z)}{\partial z} = \frac{1}{\kappa_w}\frac{\partial T_w(r,z)}{\partial t} \tag{1}$$

Where κ_w is the thermal diffusivity of water and $v(r)$ is the velocity in the well in the +z direction. In the reservoir the pertinent equation for the hydrate region is:

$$\frac{\partial^2 T(r,z)}{\partial r^2} + \frac{1}{r}\frac{\partial T(r,z)}{\partial r} + \frac{\partial^2 T(r,z)}{\partial z^2} = \frac{1}{\kappa_{mh}}\frac{\partial T(r,z)}{\partial t} \tag{2}$$

Where κ_{mh} is the thermal diffusivity of the methane hydrate and (r,z) correspond to coordinates for a point where $T(r,z) \leq T_0$ (temperature less than or equal to the hydrate melting temperature T_0 which we take as 20C for the depths considered of 1000 m. If we are in a zone where the temperature is greater than the hydrate melting temperature then the pertinent reservoir equation is:

$$\frac{\partial^2 T(r,z)}{\partial r^2} + \frac{1}{r}\frac{\partial T(r,z)}{\partial r} + \frac{\partial^2 T(r,z)}{\partial z^2} = \frac{1}{\kappa_w}\frac{\partial T(r,z)}{\partial t} \qquad (3)$$

As described by Callarotti [1] equations 3 is solved using the enthalpy method. At the surface pipe-reservoir the temperature continuity is obtained by applying the following boundary condition:

$$T_w(r_w, z) = T(r_w, z) \qquad (4)$$

When the volume considered is discretized ($\Delta r, \Delta z$) the finite difference expression for equation 1 becomes:

$$\frac{T_{wi+1,j}^k - 2T_{wi,j}^k + T_{wi-1,j}^k}{(\Delta r)^2} + \frac{T_{wi+1,j}^k - T_{wi,j}^k}{i(\Delta r)^2} + \frac{T_{wi,j+1}^k - 2T_{wi,j}^k + T_{wi,j-1}^k}{(\Delta z)^2} - \frac{v(i\Delta r)}{\kappa_w}\frac{T_{wi,j+1}^k - T_{wi,j}^k}{\Delta z} = \frac{1}{\kappa_w}\frac{T_{wi,j}^{k+1} - T_{wi,j}^k}{\Delta t} \qquad (5)$$

This scheme proved to be numerically unstable as the velocity values inside the pipe is increased. The results are shown in Figure 5.

Figure 5. Finite difference schemes results for the temperature along the pipe. As the velocity is increased the temperature shows oscillations. The continuous straight line shows the linear temperature dependence that we assumed as a boundary condition at the frontier between the pipe and the reservoir for a water velocity of 1 m/sec.
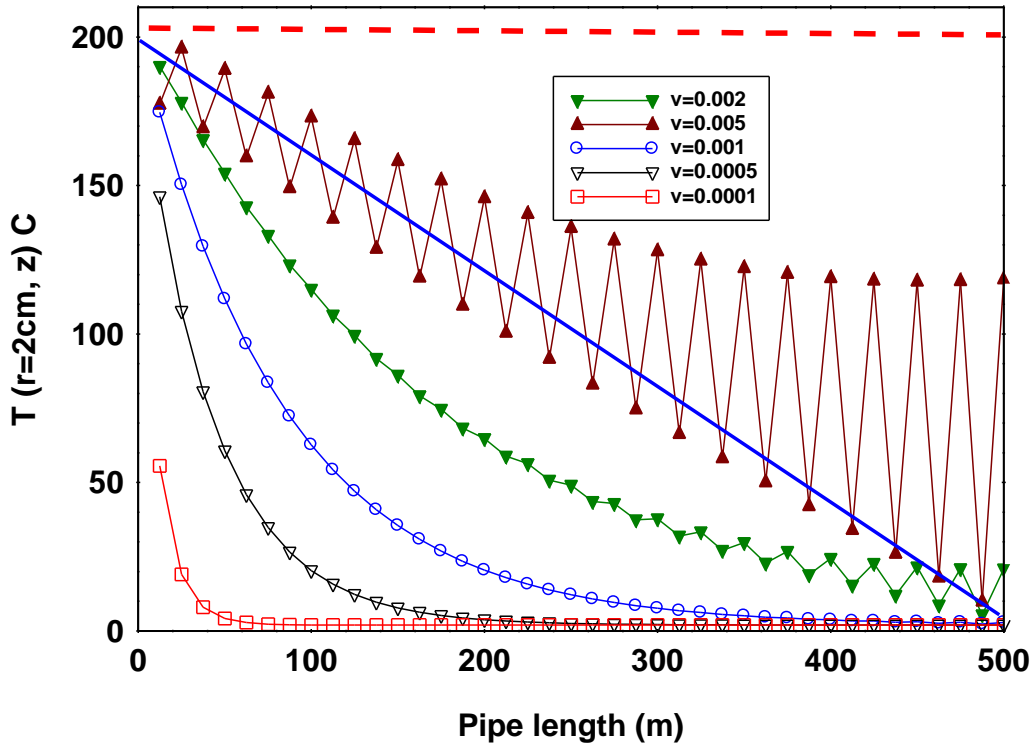
The EROI found with these straight line boundary conditions are shown in Figure 6. As expected the value of the ratio energy out /energy in will decrease with time as the reservoir is gradually heated and all the methane produced.

In the present paper we present results for the complete heat exchange problem for applied hot water, where the heat transfer is determined by solving the correct discretized equations both inside and outside the pipe, by application of Gauss theorem. This approach stabilizes the numerical procedure in the regions inside and outside the pipe allowing stable numerical solutions.

Figure 6. Plot of the EROI determined according to the two approximate reservoir boundary conditions at the interphase between the pipe and the reservoir. These solutions are obtained by conventional finite difference scheme in cylindrical coordinates.
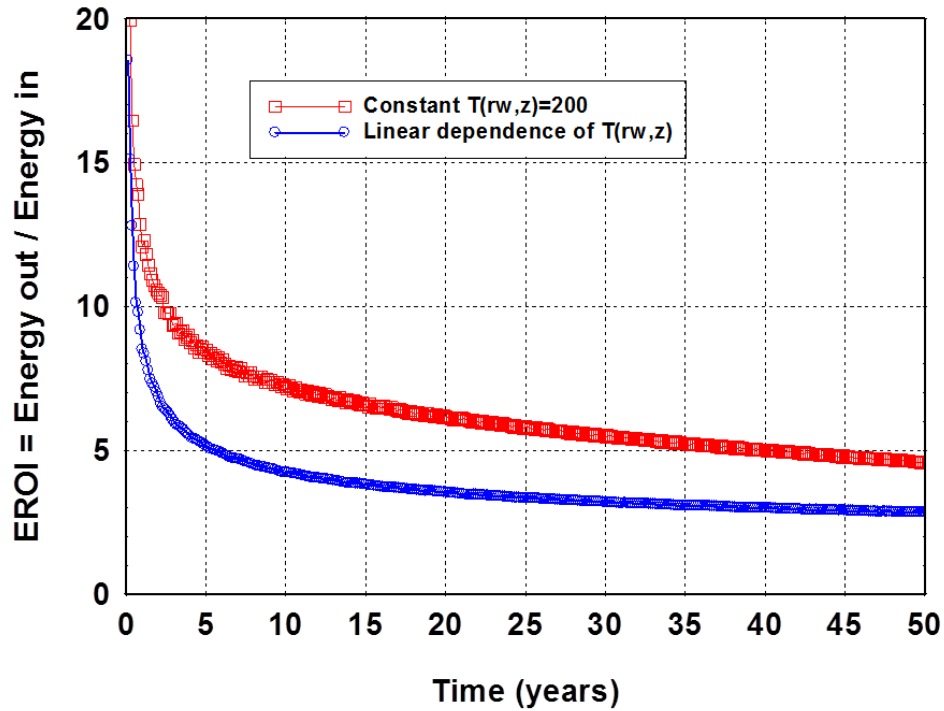
2. Gauss theorem applied to the heat transfer equations

In order to illustrate our procedure we rewrite equations 1 and 2 in order to show their general form which involves the nabla squared operator:

$$\vec{\nabla}^2 T_w(r,z,t) - \frac{1}{\kappa_w} v_z(r) \frac{\partial T_w(r,z,t)}{\partial z} = \frac{1}{\kappa_w} \frac{\partial T_w(r,z,t)}{\partial t} \tag{6}$$

$$\vec{\nabla}^2 T(r,z,t) = \frac{1}{\kappa} \frac{\partial T(r,z,t)}{\partial t} \tag{7}$$

These can be expressed as:

$$\vec{\nabla} \cdot \left[\vec{\nabla} T_w(r,z,t) - \vec{i}_z \frac{1}{\kappa_w} v_z(r) T_w(r,z,t) \right] = \frac{1}{\kappa_w} \frac{\partial T_w(r,z,t)}{\partial t} \tag{8}$$

$$\vec{\nabla} \cdot \left[\vec{\nabla} T(r,z,t) \right] = \frac{1}{\kappa} \frac{\partial T(r,z,t)}{\partial t} \tag{9}$$

We integrate over one element of volume in each region:

$$\int_{\text{volume}} \vec{\nabla} \cdot \left[\vec{\nabla} T_w(r,z,t) - \vec{i}_z \frac{1}{\kappa_w} v_z(r) T_w(r,z,t) \right] dv = \int_{\text{volume}} \frac{1}{\kappa_w} \frac{\partial T_w(r,z,t)}{\partial t} dv \tag{10}$$

$$\int_{\text{volume}} \vec{\nabla} \cdot \left[\vec{\nabla} T(r,z,t) \right] dv = \int_{\text{volume}} \frac{1}{\kappa} \frac{\partial T(r,z,t)}{\partial t} dv \tag{11}$$

We then apply Gauss theorem converting the volume integrals of the divergence of a vector to the surface integral of that vector:

$$\int_{surface}\left[\vec{\nabla}T_w(r,z,t)-\vec{i}_z\frac{1}{\kappa_w}v_z(r)T_w(r,z,t)\right]\cdot d\vec{A}=\int_{volume}\frac{1}{\kappa_w}\frac{\partial T_w(r,z,t)}{\partial t}dv \tag{12}$$

$$\int_{surface}\left[\vec{\nabla}T(r,z,t)\right]\cdot d\vec{A}=\int_{volume}\frac{1}{\kappa}\frac{\partial T(r,z,t)}{\partial t}dv \tag{13}$$

In this system we have axial symmetry: $\dfrac{\partial}{\partial\varphi}=0$, so that the gradients can be expressed as follows:

$$\int_{surface}\left[\vec{i}_r\frac{\partial T_w}{\partial r}+\vec{i}_z\frac{\partial T_w}{\partial z}-\vec{i}_z\frac{1}{\kappa_w}v_z(r)T_w\right]\cdot d\vec{A}=\int_{volume}\frac{1}{\kappa_w}\frac{\partial T_w}{\partial t}dv \tag{14}$$

$$\int_{surface}\left[\vec{i}_r\frac{\partial T}{\partial r}+\vec{i}_z\frac{\partial T}{\partial z}\right]\cdot d\vec{A}=\int_{volume}\frac{1}{\kappa}\frac{\partial T}{\partial t}dv \tag{15}$$

We discretize both regions (water and MH reservoir) with volume elements as the one shown on Figure 7.

Figure 7. An elementary volume element in cylindrical coordinates for a system with axial symmetry. The arrows indicate the directions of the r and the z axes. The magnitude and directions for each surface of the elementary volume are shown.
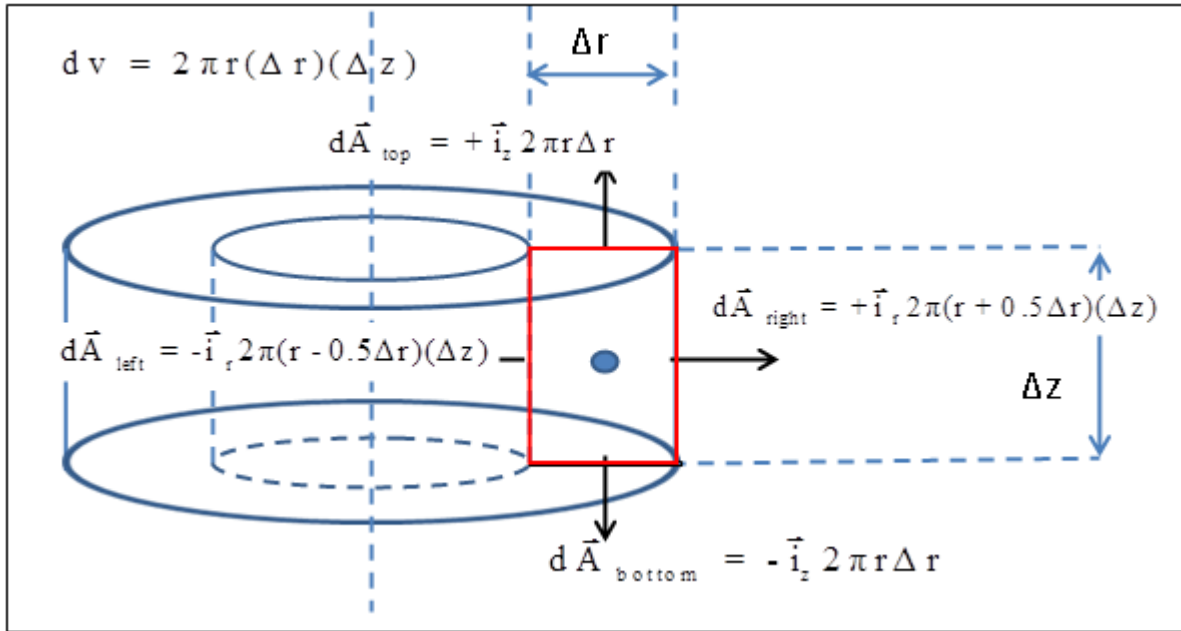
And we find:

$$\int_{surface}\left[\vec{i}_r\frac{\partial T_w}{\partial r}+\vec{i}_z\frac{\partial T_w}{\partial z}-\vec{i}_z\frac{1}{\kappa_w}v_z(r)T_w\right]\cdot d\vec{A}=\int_{volume}\frac{1}{\kappa_w}\frac{\partial T_w}{\partial t}dv \tag{16}$$

And for each surface of the water volume element we find:

$$\int_{left}\left[\frac{\partial T_w}{\partial r}\right]\vec{i}_r\cdot d\vec{A}_{left}+\int_{right}\left[\frac{\partial T_w}{\partial r}\right]\vec{i}_r\cdot d\vec{A}_{right}+\int_{top}\left[\frac{\partial T_w}{\partial z}-\frac{1}{\kappa_w}v_z(r)T_w\right]\vec{i}_z\cdot d\vec{A}_{top} \tag{17}$$

$$+\int_{bottom}\left[\frac{\partial T_w}{\partial z}-\frac{1}{\kappa_w}v_z(r)T_w\right]\vec{i}_z\cdot d\vec{A}_{bottom}=\frac{2\pi r\Delta r\Delta z}{\kappa_w}\frac{\left[T_w(r,z,t)-T_{ref}\right]}{\Delta t}\qquad T_{ref}=T_w(r,z,0^-)$$

From now on we consider that T is measured with respect to the reference temperature 2 C, and by replacing the different area elements we obtain:

$$-\int_{left}\left[\frac{\partial T_w}{\partial r}\right]\left[2\pi(r-0.5\Delta r)\Delta z\right]+\int_{right}\left[\frac{\partial T_w}{\partial r}\right]\left[2\pi(r-0.5\Delta r)\Delta z\right] \tag{18}$$

$$+\int_{top}\left[\frac{\partial T_w}{\partial z}-\frac{1}{\kappa_w}v_z(r)T_w\right]\left[2\pi r\Delta r\right]-\int_{bottom}\left[\frac{\partial T_w}{\partial z}-\frac{1}{\kappa_w}v_z(r)T_w\right]\left[2\pi r\Delta r\right]=\frac{2\pi r\Delta r\Delta z}{\kappa_w}\frac{T_w}{\Delta t}$$

Since we deal for an elementary volume element the integrals for the water region are elementarily evaluated as:

$$-\left[\frac{T_w(r,z)-T_w(r-\Delta r,z)}{\Delta r}\right]\left[2\pi(r-0.5\Delta r)\Delta z\right]+\left[\frac{T_w(r+\Delta r,z)-T_w(r,z)}{\Delta r}\right]\left[2\pi(r-0.5\Delta r)\Delta z\right]$$

$$+\left[\frac{T_w(r,z+\Delta z)-T_w(r,z)}{\Delta z}-\frac{1}{\kappa_w}v_z(r)T_w(r,z)\right]\left[2\pi r\Delta r\right] \tag{19}$$

$$-\left[\frac{T_w(r,z)-T_w(r,z-\Delta z)}{\Delta z}-\frac{1}{\kappa_w}v_z(r)T_w(r,z-\Delta z)\right]\left[2\pi r\Delta r\right]=\frac{2\pi r\Delta r\Delta z}{\kappa_w}\frac{T_w}{\Delta t}$$

For an element in the methane hydrate region we obtain:

$$-\left[\frac{T(r,z)-T(r-\Delta r,z)}{\Delta r}\right]\left[2\pi(r-0.5\Delta r)\Delta z\right]+\left[\frac{T(r+\Delta r,z)-T(r,z)}{\Delta r}\right]\left[2\pi(r-0.5\Delta r)\Delta z\right] \tag{20}$$

$$+\left[\frac{T(r,z+\Delta z)-T(r,z)}{\Delta z}\right]\left[2\pi r\Delta r\right]-\left[\frac{T(r,z)-T(r,z-\Delta z)}{\Delta z}\right]\left[2\pi r\Delta r\right]=\frac{2\pi r\Delta r\Delta z}{\kappa}\frac{T}{\Delta t}$$

This approach yields stable solutions even when the velocity is 1 m/sec when the time interval (Δt) is chosen to be small enough. Figure 8 shows the comparison between the EROI evaluated via Gauss approach, and the approximated EROI's previously discussed.

Figure 9 shows the time evolution of the applied energy and the produced energy. The applied energy is taken to be only the kinetic energy that must be applied for the water to flow with a velocity v_z:

$$KE=\frac{1}{2}\rho_{water}\left(r_w^2\right)(L_{MH})v_z^2 \tag{21}$$

The Figure clearly shows the stepwise behavior of the produced energy, as it takes time for the applied energy to heat up each volume element above the melting temperature. As time progresses, it takes longer to heat each volume element since these methane hydrate elements are located at increasing distances from the heating pipe and their volume increases accordingly. Eventually the produced energy will reach a plateau when all the methane hydrate has melted.

Figure 8. Comparison of the EROI determined via Gauss approach, vs approximated EROI. The energy gain is significant over an extended time span.
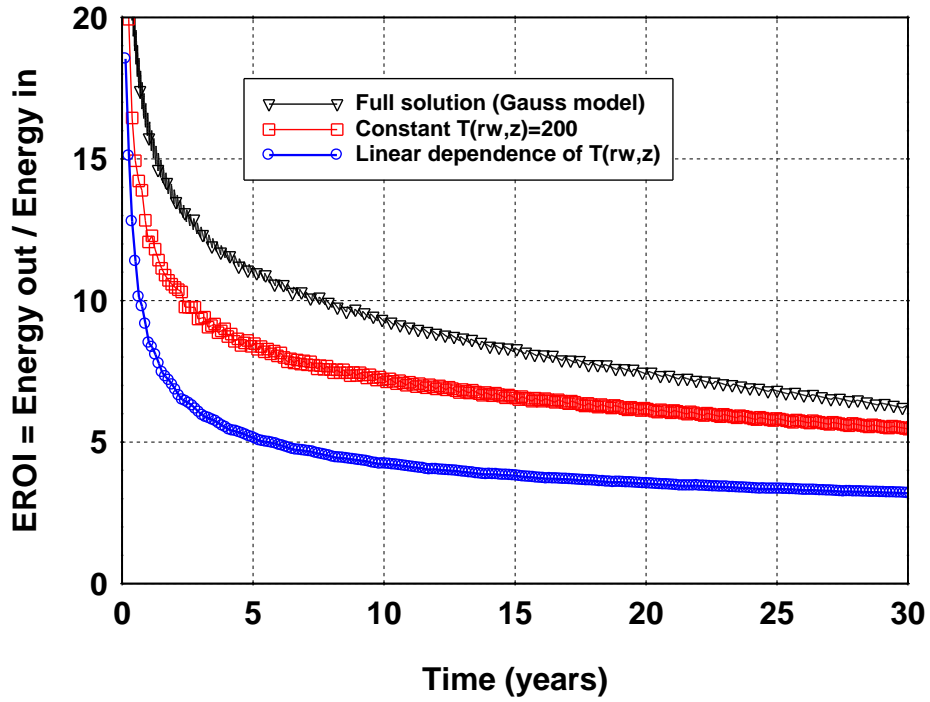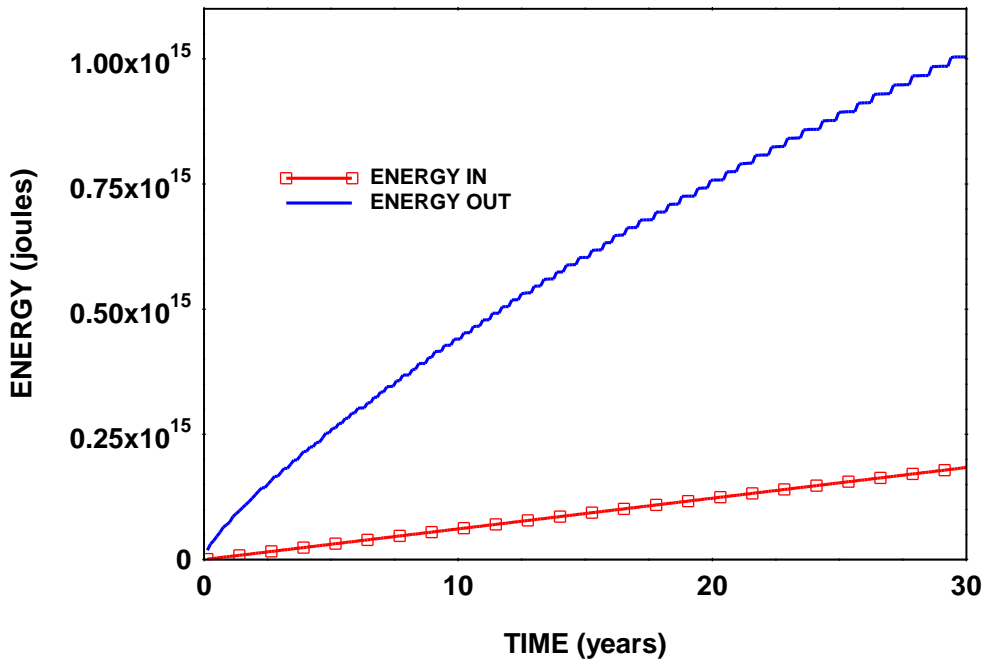

Figure 9. Plots of the applied energy vs. time and the energy equivalent of the melted sections of methane hydrates..

4. Conclusions

We have considered the change of phase of the solid methane hydrate into water and methane gas when the temperature of each volume element is greater than a melting temperature of 20 C. This is the

temperature of the MH phase diagram edge at 1000 meter depths [1]. The energy produced is taken to be of the order of 6.1x10+9 joules for each cubic meter of methane hydrate, which dissociates into 160 cubic meters of gas at STP conditions (published data indicates a methane heat of combustion of 3.868 x 107 joules/m3 , in close agreement with reported methane energy content of 1000 BTU per cubic foot). The results obtained for an initial water temperature of 200 C, indicate an EROI [(Energy out) / (Primary energy in)] which varied from 30 as the production is started, to 7 after 30 years of production. The primary input energy was the kinetic energy of the water flow into a pipe of 1 m diameter with a 1 m/sec vel. The thermal energy required to heat the water was assumed to be generated in the cogeneration processes considered in the Japanese production scheme [4].

Acknowledgments

Conflict of Interest

The author declares no known conflict of interest

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