

Complexities of Natural Gas Hydrates as an Energy Resource and its relation with Climate Change

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Abstract

The ever-growing energy demands, declining oil prices, dwindling new findings of oil/gas reservoirs, complexity, and uncertainty associated with unconventional oil/gas supplies; and the seriousness towards mitigating the greenhouse gas emissions essentially implies the risky and uncertain nature of future energy at the global scale. Such a risky and complex pathway has made the exploration of unconventional hydrocarbons resources such as natural gas hydrates one of the potential alternatives that can significantly contribute to the growing energy demand. There is a huge gap between the experimental investigations and its associated up-scaling to a larger field-scale as these gas hydrates are generally located in highly remote places such as polar- and marine-environments. Thus, more studies are still required towards the field-scale exploration and production of gas-hydrates with their associated environmental, economic, and social consequences. In this context, an attempt has been made in order to list out the practical difficulties that are experienced during the exploration and production of natural gas hydrates as a possible and new energy resource given the constraints associated with the conventional fossil fuels. These complexities associated with the real field-scale production of gas hydrates are expected to provide improved insights for experimental scientists working on gas hydrates. In addition, the way the natural gas hydrates gets associated with climate change has been discussed in detail, and critical conclusions have been drawn.

Keywords: *Gas hydrates; Energy demand; Field-scale; Exploration and production; Climate-change.*

1. Introduction

Methane gas hydrates consist of methane-gas and water in a solid phase, and it remains stable at relatively high pressure and low temperature. Most of the global methane content (or the mobile organic carbon) is associated with these gas hydrates. However, exploration and production of these gas hydrates are not as easy as conventional fossil fuels, while they need to be extracted from relatively remote and harsh polar- and marine environments. Gas hydrates were first developed at the laboratory-scale by experimental means in the early 1800s. Most of the following experimental investigations (for nearly two centuries) and their forecast failed to up-scale the observed processes from the laboratory-scale to the larger field-scale, and it essentially remained as an academic interest. However, the blockages of oil/gas pipelines by the gas hydrates were well understood; and the scientific community really helped in addressing such industrial hazards. The natural occurrence of gas hydrates was first observed by Russian scientists in the 1960s, and subsequently, the scientific community started realizing the abundance of gas hydrates in a natural environment. The passion for the exploration and production of natural gas hydrates started increasing exponentially as the elevation in the mean global temperature (global climate change) has a direct correlation with these methane-gas fractions. In this context, the concept 'flow assurance' associated with the 'industrial-hazard' (unwanted gas hydrate formation during transportation through pipelines) was being given more importance, while the 'natural-hazard' associated with the exploration and production of natural gas hydrates in deepwater remained very less focused due to their

associated complexities and practical difficulties. Given this background, the objective of the present work is to investigate the practical feasibility of the use of natural gas hydrates as an energy resource in the context of growing energy demand with depleting conventional fossil fuels [1].

2. Evolution of gas hydrates

The first gas-hydrate (water and gas was coupled to produce a solid substance) was created in the laboratory by Sir Humphry Davy in 1810, while Faraday made an attempt to measure the composition of gas hydrates for the first time around 1800. In 1850, it was first realized that the gas hydrates have a complex relationship between pressure and temperature (at which they are stable), unlike the pressure-temperature correlations associated with the conventional oil and gas. In the early 1930s, as the natural gas was used as a fuel, this gas was transported through the pipelines; and eventually, the flow assurance problem (plugging of the pipe flow by gas-hydrates which are not ice) was at its peak, where the methane gas hydrates were formed in the gas pipelines and blocked the smooth flow of the fluid through the pipeline transportation. In addition, the problem of flow assurance started gaining interest as the exploration of hydrocarbon gases got associated with deeper water, where these hydrates form easily. Also, the chemical nature of the gas hydrates was understood in detail using X-ray diffraction, and the concept of 'clathrates' (solids without a proper chemical composition, in which relatively smaller guest molecules are trapped within the solid host lattice) came into the picture around 1940. Thus, the scientists realized the importance of thermodynamics along with the conventional fluid dynamics used to characterize the fluid flow through pipelines as the gas hydrates were very sensitive to the reservoir temperature (and pressure). Thus, it paved the way for the development of many thermodynamic models for investigating the various properties of natural gas hydrates based on the crystal structure information observed from the X-ray diffraction. The research was then focused on the 'stability' of gas hydrates having secured the gas hydrate properties. Following the flow assurance problem, and having realized the natural association of methane gas with water under the favourable conditions of relatively higher pressure and lower temperature, scientists in the mid-1960s started finding the occurrence of gas hydrates by natural means as against the creation of gas hydrates in the laboratory. Thus, the presence of gas hydrates on various natural gas hydrates reservoirs (a) in the permafrost regions; and (b) in the marine environment found either in shallow sea-floor sediments or in the sediments (including sub-marine land-slides) clearly conveyed that gas hydrates are abundant in the continental margin and slope-sediments, and profuse availability leads to the studies that correlate the methane-gas of gas hydrates with the climate change (that included the exchange between the methane-gas and CO₂). In essence, the investigations on gas hydrates were only at the laboratory-scale using experiments until the 1980s, while the problem got associated with the field work (not at the field-scale) by means of addressing the blockage of gas pipelines by gas hydrates during its transportation through gas pipelines from late 1930s. The concept of natural gas hydrates as an 'energy resource' and its associated consequence to its 'environment' remained focus from the late 1970s following the concept of deep-sea drilling; and eventually, gas hydrates were acknowledged as an essential part of the natural environment; while also realizing that the gas hydrates energy potential could have a direct correlation with the societal-implications.

3. Complexities of gas hydrates

1. Detection of gas hydrates remains difficult as it requires an inimitable blend of higher-pressure with lower-temperature for their stability, and accessing such places (beneath permafrost & in the marine-sediments of continental-margins) remain still more difficult.
2. The collection of gas hydrates by means of smaller solid masses from in-situ marine sediments will abruptly disappear upon their arrival to the inspection deck as the rate of phase change associated with the gas hydrates are very rapid. The sediment samples recovered from gas-hydrate reservoirs will not be having the same characteristics as seen in the reservoir because the reduction in pressure and the enhancement in temperature upon the

- arrival at the surface conditions results in either partial or complete dissociation of massive gas hydrates.
3. There is no fixed ratio of gas-molecules to water-molecules for gas hydrates.
 4. There is no fixed number of guest molecules that will physically stabilize the host molecules.
 5. There is no chemical bonding between the guest and host molecules.
 6. There is no necessity that all the cages of the solid host lattice must be occupied by the guest molecules for the stability to happen.
 7. There is no uniformity among the various cages with which they are getting occupied by the guest molecules, and it depends on temperature, pressure apart from the gases present.
 8. There is no fixed chemical composition for gas hydrates, and hence are non-stoichiometric by nature for a given pressure and temperature.
 9. It is not mandatory that methane must be the clathrate guest molecule apart from the lattice building water molecule (a variety of gases can be fitted within the clathrate structures); and the guest molecule can be ethane, propane, nitrogen, or carbon-di-oxide having low-molecular weights. However, Structure I hydrate (a clathrate structural formation with dominant methane) is very common in comparison with Structure II (a clathrate structural formation with dominant ethane or propane) and Structure H.
 10. The stability conditions are not similar for ice and methane-hydrates, albeit with their chemical similarities. The stability of ice depends on temperature, while the stability of methane-hydrates depends on pressure, temperature, chemical composition & abundance of the guest molecule; and the chemistry of water.
 11. Hydrates cannot exist at depths where the temperature exceeds the maximum stability temperature for gas hydrate.
 12. The presence of gas hydrates cannot be ensured just by ensuring that the given location fulfills the temperature and pressure requirements of gas hydrate stability.
 13. The distribution of gas hydrates does not remain uniform because of (a) the total amount of pore volume available for gas hydrates in the stability zone; (b) the permeable paths of liquid and gaseous phases; (c) the fraction of the pore volume occupied by gas hydrates known as the gas hydrate saturation, and (d) the physical/chemical/biological conditions that govern the transformation of organic materials into methane-gas – can fluctuate intensely over small distances; and in turn, have made the estimation on the global distribution of gas hydrates to be too complex.
 14. The global methane content (accounting nearly one-third of the global organic carbon) associated with the gas hydrates remains difficult to estimate precisely; and the available range varies in between $10^3 - 10^4$ giga-tonnes of carbon; and thereby clearly reflecting the uncertainties associated with the amount of actually transported methane-gas against the methane-gas that has been stored in Gas Hydrate Stability Zone (GHSZ).
 15. There cannot be uniform accessibility of all the available gas hydrates that are considered to be an energy resource.
 16. The formation and growth of gas hydrate mounds (initiated by the active fluid vents/seeps) on the sea floor has to sustain the erosive forces exerted by the volume of seawater apart from the temperature fluctuations that will destabilize the formation of gas hydrates or dissolve the uncovered the gas-hydrates.
 17. The occurrence of gas hydrates is associated with fine-grained sediments such as clays and muds, whose pore-sizes are extremely small. Such microscopic pore sizes reduce the permeability significantly. These gas hydrates are generally found dispersed, occupying roughly around 1- 10% of the total pore volume. Fractured clay sediments, off the coast of eastern India; and the east sea of Korea - had a relatively larger gas hydrate saturations (20 – 30%); and it remains distinct. Since the specific weight of gas hydrates is relatively smaller, the buoyant force plays a critical role in the resultant vertical migration as against the conventional horizontal migration by the liquid phases. Thus, the presence of gas hydrates is associated with a thin fracture network having a dominant vertical direction.

18. It is not mandatory that the gas hydrates will occur only with the presence of Bottom Simulating Reflectors (BSRs); and hence, BSRs do not remain as the reliable indicator on the concentration of gas hydrates.
19. It requires advanced technologies that will let the samples to be gathered and recovered without disturbing the natural stability of those gas hydrates; and from such data, the correlation between the occurrences of gas hydrates with their in-situ sediment's physical/chemical properties can be deduced with precision.
20. It remains highly challenging when delineating the stability boundary for gas hydrates involves the segregation of (a) Sea floor mounds zone; (b) Methane depleted zone; (c) Upper edge stability zone that is sensitive to climate; (d) Zone of permafrost; and (e) Varying sedimental zones (such as hydrate-bearing marine-clays and deformed-clays; and hydrate-bearing sands) that displaces gas hydrates from beneath the sea floor.
21. The way the gas hydrates suit into methane's contribution to the cycle of carbon movement between the biosphere, geosphere, hydrosphere, and atmosphere is too complicated.
22. It remains challenging to precisely estimate the amount of carbon released from gas hydrates into the atmosphere and its associated link with the global climate changes.
23. Albeit methane stands third among the most-abundant greenhouse gases, it is roughly 20 times more dangerous than CO₂ as the methane absorbs and traps the heat that radiates from the earth's surface. However, the carbon cycle becomes too complex as the atmospheric methane gets converted back to water and CO₂ in the presence of sunlight during its short stay in the atmosphere (roughly 10 years).
24. It remains challenging to deduce the factors that are conducive to the enhancement in the methane-gas fluxes to the atmosphere (from 700 ppb before 1750 to nearly 2000 ppb as of date based on nearly 0.5 Giga-tonnes of methane-carbon emitted to the atmosphere per annum) as the spatial and temporal differences of the measured methane-gas fluxes do not remain to be insignificant. However, it is believed that only one percent of the annual methane-gas emission is associated with gas hydrates.
25. The physical, chemical, and biological processes associated with gas hydrates in enhancing the transport of methane-gas from the sea-floor to the atmosphere still remains complicated.
26. The estimation of methane flux (getting into the atmosphere) from gas hydrates alone remains challenging as there are several means of methane-gas emissions getting into the atmosphere that includes from (a) wetlands; (b) ruminant emissions; (c) burned fuels from oil & gas; (d) burned fuel from coal; (e) rice paddies; (f) land-fills; (g) termite emissions; (h) wild animal emissions; (i) biomass burning; (j) geological resources; (k) oceans; and (l) wildfires.
27. Despite the favourable conditions associated with the sediments of deep ocean temperature and pressure for the formation of gas hydrates, most of the global gas hydrate is associated with continental margins, where the rate of organic-carbon burial is significantly larger.
28. Not all the hydrocarbons (resulting from leakage of deep gas reservoirs; from reservoir over-pressurization; released from salt dome structures; released from mud volcanos; or released from continental-scale tectonic activities), which were formed beneath the sea floor will be able to migrate upwards towards the sea floor through the high permeable fractures or faults vertically due to its associated buoyant force. The vertically migrating methane gases will get trapped during its vertical migration as the thickness of the fractures or faults will have near-zero thicknesses at some locations; and such trapped gases become gas hydrates, while the other fraction of methane gases may be traversing up to the sea floor as they travel through a relatively larger fracture aperture. Thus, a knowledge of fracture geometry (and their distribution) that includes horizontal fracture length, vertical fracture length, fracture thickness, fracture width, fracture spacing, and fracture dip is required in order to deduce the details on whether the released gases from the marine-sediments would remain trapped as gas hydrates in the fractures itself or will it be released as gases at the sea floor.

29. The complex interplay between the oxidation processes associated with the atmosphere as well in the marine sediments makes the estimation of methane-fluxes too challenging. It is not clear whether the presence of methane can be all-together excluded from the carbon cycle as the photolytic process oxidises methane to CO₂ in the atmosphere, while anaerobic oxidation (either by methanotrophic archaea or by sulphate reducing bacteria) oxidises the methane associated with the marine sediments. In essence, methane-gas associated with gas hydrates may not be the primary dependent variable of interest, and it may rather act either as a source (when methane influx to gas hydrates exceeds the methane efflux from gas hydrates in the presence of significant pore-water) or a sink. The influx pertains to the entry of methane-gas into the GHSZ by the degradation of organic carbons; and its subsequent production and mobility of methane. The efflux pertains to the left of methane from gas hydrates by dissociation and dissolution of gas hydrates along with anaerobic oxidation.
30. It is relatively difficult to deduce the fraction of methane that is getting lost (before it reaches the atmosphere) individually by methane-consuming microbes in marine sediments as well as those microbes that reside in the sea water column, while it is also not clear to deduce the fraction of methane associated with aerobic and anaerobic oxidation processes that lead to acidification of the sea water (by reducing the pH values).
31. The pressure distribution associated with the dissociation of gas hydrates in marine sediments is relatively difficult to estimate using the principle of Terzhagi's consolidation theory as it requires the details not only on the enhancement in pore pressure but also on the corresponding reduction in grain stress that weakens the marine sediment. The gas hydrate dissociation process becomes complex even upon assuming constant over-burden stress because the released gaseous-phase methane-gas and liquid-phase water – upon the dissociation of gas hydrates - occupy a volume that is greater than the original volume of the gas hydrate; and the estimation of the resulting volume increase remains highly challenging. Such gas-hydrate dissociation with realignment in pressure distribution leads to continental-slides (sub-marine slides), especially during the pressure drop following an earth-quake or the pressure drop resulting from a reduction in sea water level or the pressure drop resulting from the enhanced bottom-water temperatures.
32. It is also possible that there may not be an equilibrium between the increase in pore-pressure with the corresponding reduction in grain stress for constant over-burden stress – upon the dissociation of gas hydrates – as a significant fraction of methane-gas and water released from the dissociation of gas hydrates is pushed away from original the volume of interest (the components moving out of control volume). Thus, the estimation of enhancement in pore pressure in such cases using conventional consolidation theory may lead to incorrect results; and subsequently, making the locations of gas hydrates and their associated location of land-slides / glide-planes to be too complicated.
33. The characteristics of methane emission from cold-seep environments remain distinctly different from the hot-seep environments (such as hydrothermal vents located along with the mid-ocean ranges). Thus, the areal spreading of methane-release on the sea-floor bed; and the fraction of methane-release that gets dissolved in the water column differ significantly for cold-seep and hot-seep environments.
34. There are no explicit reserves (confirmed and quantified economically recoverable resources) for gas hydrates as of the date in the world due to the lack of production potential on a long-term basis (no commercial-scale extraction so far but may likely improve). Further, characterizing the methane flow from fracture-filling gas hydrate reservoirs will remain too complex as the understanding of the geo-mechanical stability of the gas-hydrate/sediment formation along with their well-bore assembly require the methane-flow to be characterized by a non-Darcian approach at a scale that is much smaller than the continuum.
35. The extraction of gas hydrates requires unconventional recovery processes and technologies in order to extract it economically (in the future). It remains extremely challenging even to extract a small fraction of the methane-gas that is associated with gas-hydrates

- (which is technically as well as economically feasible), although the rough estimation of global gas hydrates hangs around 20,000 trillion m³. Unlike conventional hydrocarbon resources, the gas hydrates in-place resources drastically vary over the geological time period.
36. The extraction of gas hydrates becomes complex as dominant gas hydrate reservoirs have been housed in clays than sandy-silt deposits. Clays have extremely low permeability despite having a relatively larger porosity; and thereby, clayey gas hydrate reservoir lacks the driving force necessary for the gas hydrates to get them transported towards the production well. Further, even the permeability in sand-rich gas hydrate reservoirs drops down drastically upon the formation of hydrates; and thereby making the extraction of gas hydrates to be too complex.
 37. Site survey, foundation, drilling, completion, and production operations remain extremely difficult for the gas hydrate reservoirs that are located within the permafrost as the temperature always remains sub-zero for an onshore reservoir with sand-rich sediments. However, the above operations remain relatively easier when the gas hydrate reservoir is located beneath the permafrost, where the temperature hangs around 0 – 14° C. When the gas hydrate reservoir's sediments contain materials other than sands, then all the above field operational processes remain extremely difficult (or nearly impossible) whether it is onshore or offshore. Extraction of gas hydrates from marine-sediments somewhat looks positive for a shallow reservoir with sandy sediments, while the complexity increases for the deep reservoirs. And, for muddy marine sediments, the drilling & production poses great challenges.
 38. Dissociation of gas hydrates being endothermic, the depressurization technique suppresses the formation temperature to the extent that it may impede the dissociation process itself. On the other hand, if the depressurization technique leads to pressures that are lesser than the quadruple point of the hydrate, then liquid-phase pore-water gets frozen; and hence, the depressurization technique has a strong correlation with the initial reservoir conditions in addition to the control on bottom-hole-pressure.
 39. Gas hydrate production at field-scale using chemical injection is limited as it requires an enormous volume of chemicals to be injected into a reservoir that may cost heavily. On the other hand, since a large amount of water is released during the dissociation of gas hydrates, the effectiveness of the applied inhibitors keep declining drastically.
 40. During gas hydrate production from an unconsolidated formation, there will be a significant sand inflow towards the well-bore as the unconsolidated sediments easily lose their strength upon the dissociation of gas hydrates.

4. Gas hydrates and climate change

1. Although the radiative capacity (earth's energy balance as a function of incoming and lost solar energy) of methane (0.5 W/m²) remains smaller than CO₂ (1.66 W/m²), methane still remains more dangerous than CO₂. These radiative forces are used to estimate the relative impacts of climate-induced from the disturbances associated with earth's radiation; and provide a correlation between the global mean force and the global mean surface temperature (@ equilibrium).
2. The influence of methane emission into the atmosphere is not only related to the radiative capacity of methane, while it strongly depends on the time-scale associated with the removal of methane from the atmosphere (an average of 10 years of residence time in the atmosphere for methane, during which, it produces ozone, water-vapour, and CO₂) considering the existing thermal budget as well as the Global Warming Potential (GWP: Ratio between the time-integrated radiative forcing term from the instantaneous release of 1 kg of methane to that of 1 kg of a reference gas) of methane. The atmosphere roughly contains about 4 giga-tonnes of methane carbon, while both the influx and efflux of methane carbon per annum hang around 0.5 giga-tonnes.

3. Gas hydrates contain nearly 5000 giga-tonnes of carbon in the form of sequestered methane in the subsurface, out of which nearly 0.1% of gas hydrates from the subsurface/ocean is released into the atmosphere.
4. When methane is released into the ocean through the sea floor, methane gets oxidized in the water column to CO₂. During this process, there is a significant loss of dissolved oxygen. Also, the ocean gets acidified by the release of CO₂; and thus, ocean acidification remains the primary consequence of gas hydrate dissociation [2].
5. Temperature estimation is crucial in order to assess the "intensity and spatial/temporal distribution" of global warming. The details on the temperature evolution of the buried gas hydrates either in marine sediments remain vital. For this purpose, the data on the variations in sea water level, polar glacier masses, and ocean circulation are required in order to estimate the temperature variations on the sea floor (or on the coastal permafrost regions) from the mean surface temperature.
6. Any changes in mean surface temperatures can be correlated with the number of buried gas hydrates that may be broken down resulting from the respective temperature fluctuations on the sea surface. It needs to be verified whether the regions with enhanced mean surface temperature have the respective enhancement in the breaking down of buried gas hydrates. If so, the respective depth of occurrences needs to be reordered in order to deduce the correlation between the local thermal-gradient with the local warming.
7. The time taken for the destabilization of gas hydrates by the temperature variations in the respective sediment deposition is very critical. The rate of heat transfer is mitigated not only by the heat transportation through sediments; but also by the dissociation of gas hydrates themselves. Thus, there should be a correlation between (a) mean surface temperatures; (b) local thermal gradient in the sea water column; and (c) the thermal gradient associated with the sediment deposition in order to assess the actual time taken by the warming that destabilizes the buried gas hydrates either partially or completely.
8. The estimation of released methane gas from the destabilized gas hydrates remains critical as a fraction of it will always either be consumed or dissolved depending on the location.
9. Since dissociation of gas hydrates is sensitive to the warming of bottom waters in the sea floor, it is crucial to deduce a correlation between the increase in mean global temperature with increase in mean sea floor bottom temperature - in shallow water systems. Since a column of sea water (with a relatively higher specific heat capacity) is present in between the atmosphere and the bottom of the sea floor, the way the temperature gets dispersed vertically will play a critical role in deciding the resultant sea floor bottom temperature; and in turn, it will dictate the resultant dissociation of gas hydrates associated with the sea floor bottom water warming. The heat transfer mechanism should consider thermal dispersion in m²/day (which is the product of thermal dispersivity in meters for the given height of the sea water column; and the fluid velocity of the local ocean current in m/day) also in addition to considering thermal conduction and thermal convection. Thermal dispersion reflects whether the vertical sea water column contains fluid regimes with more or less similar fluid velocities across the entire vertical stretch (pertaining to the smaller value such as 0.01 or 0.1 depicting a nearly homogeneous system associated with the vertical sea water column) or the fluid velocity in the given vertical stretch varies a lot as a function of fluid depth (pertaining to relatively larger values such as 1 – 100 depicting significant heterogeneity associated with the vertical sea water column). It is the thermal dispersion that will precisely estimate the amount of heat that has been dispersed through vertical convection as well as vertical mixing during its convection from the sea surface to the sea bottom. However, the conduction of heat from the bottom-water to the buried sediments may take thousands of years, albeit the upper sediment layers remaining within the GHSZ. The magnitude of thermal conductivity (around 1.1 – 1.3 W/m/K); the volumetric thermal heat capacity (around 4.5 – 6 J/cm³/K); and the initial geothermal gradient (around 35 – 45 degrees C/km) remain sensitive in deciding whether the methane-gas hydrates remain stable or not, depending on whether the ambient sediment temperature remains lesser than or greater than the temperature defined by the phase boundary. In addition, the

relevance of heat transfer by conductive mode between the bottom-water and the buried sediments would remain insignificant under deepwater settings (as only the deepest gas hydrate dissociates).

10. The relation between the thickness of GHSZ resulting from global warming requires further investigation as the enhancement on ocean acidification, and oxygen depletion seems reasonable, while the enhancement on global warming from the released methane into the atmosphere needs to be quantified explicitly - apart from quantifying the rate of methane oxidation.
11. The gas-hydrate deposits associated with the Deep-water marine environment (exceeding 500 m of water depth) remain the major source of gas-hydrate deposits with reference to (a) Upper continental slope environments (300 – 500 m depth); (b) Terrestrial arctic environments; (c) Flooded permafrost environments (Lesser than 100 m depth); and (d) Gas-hydrate mounds on the sea-floor.
12. The emission of methane that gets into the atmosphere, released from the dissociation of gas hydrates, remains insignificant, at least for few more decades. Even if it is released, a significant fraction of methane will be consumed before it gets into the atmosphere.
13. The methane release patterns (with the details on methane release rate and the volumetric-scales of methane release) from varying sources such as the methane-release from (a) gas hydrate dissociation; (b) from deeper hydrocarbon reservoirs; and (c) from the decomposition of organic-material – needs to be analysed in detail in order to better estimate the methane-influx into the atmosphere [3].

5. Conclusions

The following conclusions have been drawn from the present study.

1. Detailed knowledge of fracture- network/geometry (and their distribution) that includes horizontal fracture length, vertical fracture length, fracture thickness, fracture width, fracture spacing, and fracture dip is required in order to deduce the details on whether the released gases from the marine-sediments would remain trapped as gas hydrates in the fractures itself or will it be released as gases at the sea floor.
2. The methane-gas associated with gas hydrates may not be the primary dependent variable of interest, and it may rather act either as a source (when methane influx to gas hydrates exceeds the methane efflux from gas hydrates) or a sink.
3. The gas hydrate dissociation process becomes complex even upon assuming constant overburden stress because the released gaseous-phase methane-gas and liquid-phase water – upon the dissociation of gas hydrates - occupy a volume that is greater than the original volume of the gas hydrate; and the estimation of the resulting volume increase remains highly challenging.
4. The influence of methane emission into the atmosphere is not only related to the radiative capacity of methane, while it strongly depends on the time-scale associated with the removal of methane from the atmosphere considering the existing thermal budget as well as the Global Warming Potential of methane.
5. A correlation between (a) mean surface temperatures; (b) local thermal gradient in the sea water column; and (c) the thermal gradient associated with the sediment deposition is required in order to assess the actual time taken by the warming that destabilizes the buried gas hydrates either partially or completely.
6. The intensity of warming; the location of warming; the number of gas hydrates that are broken down from the warming; the duration of the warming period required to destabilize the gas hydrates; the amount of methane that is released from the destabilized gas hydrates; and the amount of methane that is actually transferred to the atmosphere – all these data are required for an improved understanding on the correlation between gas hydrates and climate change.
7. Since the intensity and the timing of the induced methane emission from dissociating gas hydrates remains poorly understood, the correlation between gas hydrate dissociation and global warming in the next few decades needs further investigation.

8. Thermal dispersion, which is the product of thermal dispersivity in meters (for the given height of the sea water column) and the local fluid velocity of the ocean current (m/day), should also be considered in addition to considering thermal conduction and thermal convection while estimating the amount of heat that has been dispersed through vertical convection as well as vertical mixing during its convection from the sea surface to the sea bottom; and this improved estimation of sea floor bottom-water temperature will help to better estimate the induced gas hydrate dissociation in shallow water systems.
9. For assessing the long-term impact of climate change, various sources of transient methane emissions at their respective release-rates needs to be identified while carefully excluding the methane release associated with the long term sediment warming by sea water flooding; and such estimation requires the details on the methane removal by dissolution as well as by microbes both in the marine-sediments as well as within the sea water column. In addition, these estimates should be carried out separately for (a) methane-emission from deeper hydrocarbon reservoirs; and (b) methane-emission from the dissociation of gas hydrates by warming.

This study is expected to provide improved insights for experimental scientists working on gas hydrates at the laboratory-scale to have a feel on the real field-scale exploration and production of natural gas hydrates while also providing an opportunity to correlate the various possible sources of methane emission with the current and future climate change.

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