Energy Conversion and Management 86 (2014) 325–339

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

A general-purpose process modelling framework for marine energy systems

George G. Dimopoulos, Chariklia A. Georgopoulou, Iason C. Stefanatos, Alexandros S. Zymaris, Nikolaos M.P. Kakalis *

Det Norske Veritas Research & Innovation, 5 Aitolikou Str., Piraeus 18545, Greece

ARTICLE INFO

Article history:
Received 24 July 2013
Accepted 13 April 2014

Keywords:
Marine energy systems
Systems engineering
Process modelling
Simulation
Optimisation

ABSTRACT

High fuel prices, environmental regulations and current shipping market conditions impose ships to operate in a more efficient and greener way. These drivers lead to the introduction of new technologies, fuels, and operations, increasing the complexity of modern ship energy systems. As a means to manage this complexity, in this paper we present the introduction of systems engineering methodologies in marine engineering via the development of a general-purpose process modelling framework for ships named as DNV COSSMOS. Shifting the focus from components – the standard approach in shipping- to systems, widens the space for optimal design and operation solutions. The associated computer implementation of COSSMOS is a platform that models, simulates and optimises integrated marine energy systems with respect to energy efficiency, emissions, safety/reliability and costs, under both steady-state and dynamic conditions. DNV COSSMOS can be used in assessment and optimisation of design and operation problems in existing vessels, new builds as well as new technologies. The main features and our modelling approach are presented and key capabilities are illustrated via two studies on the thermo-economic design and operation optimisation of a combined cycle system for large bulk carriers, and the transient operation simulation of an electric marine propulsion system.

1. Introduction

Shipping transports over 85% of world's merchandise with a fleet of more than 50,000 merchant ships. Rising fuel costs, shipping market volatility, existing and upcoming environmental regulations impose a pressure on marine vessels to be designed and operated in a more efficient, cost-effective, and environmentally friendly way. The propulsion power and energy conversion on-board installation is the main contributor to the overall efficiency and emissions footprint of the vessel. To meet those stringent and often contradicting requirements, the sophistication and complexity of modern marine energy systems increase, while often operating close to the design limit. However, any complexity increase in shipping is, in principle, undesirable for safety considerations. Therefore, global assessment of performance, safety, and reliability of marine systems under real service conditions and transient operation modes becomes increasingly important for the shipping industry. To date, however, there is no formal methodological framework and consistent practical approaches to effectively manage this complexity in a holistic way.

Traditional approaches focus on improving efficiency via the optimisation of individual machinery components. With today's maturity of equipment technology, in order to achieve step-change improvements in both existing and new marine energy systems, new approaches need to be adopted for systems configuration, design, operation and control that consider machinery and energy conversion from the integrated systems' perspective. In that respect, the introduction of systems-level modelling, simulation and optimisation methods to the marine industry appears to be the next step to manage the increasing complexity of marine machinery systems. Although this is novel for the marine industry, significant experience can be drawn from process systems engineering, where these approaches have proven to be a game changer in the chemical/process industry with applications spanning from the nano- and micro-scales to enterprise-wide supply chain management.

In this work, we present a general purpose modelling framework for marine systems engineering. First, its main specifications are given, followed by the mathematical formulation pertinent to the generic process modelling of the physical phenomena within

* Corresponding author.
E-mail address: Nikolaos.Kakalis@dnv.com (N.M.P. Kakalis).

http://dx.doi.org/10.1016/j.enconman.2014.04.046
0196-8904/

Nomenclature

Latin symbols

A	area (m^2)
c_i	molar concentration of species i (mol/m^3)
c_{p4}	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
D_i	diffusivity coefficient of species i (m^2/s)
f	frequency (Hz)
F	Faraday's constant
h	specific enthalpy (J/kg)
h_{HT}	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
$\mathbf{I}$	electric current matrix (A)
I_{mm}	mass moment of inertia ($kg\ m^2$)
j	electric current density (A/m^3)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
$\mathbf{L}$	physical inductance matric (H)
L	length (m)
M	torque (N m)
$\dot{m}$	mass flow rate (kg/s)
$\mathbf{p}$	set of parameters
p	pressure (Pa)
PF	electric power factor ($\cos\varphi$)
Pr	Prandtl number (–)
$\mathbf{R}$	electrical resistance matrix (Ω)
r_j	rate of the reaction j (mol/s)
Re	Reynolds number (–)
T	temperature (K)
$\mathbf{x}$	molar composition (species vector)
$\mathbf{X}$	set of algebraic variables
$\mathbf{Y}$	set of time-differential variables
$\mathbf{u}$	set of control variables
$\mathbf{U}$	electric voltage matrix (V)
u	velocity (m/s)
u_V	volume specific internal energy (J/m^3)
V	volume (m^3)
$\dot{W}$	power (W)

Greek symbols

ΔH	enthalpy of reaction (J/mol)
ε	emissivity factor
ζ	momentum conservation source term
ν_{ij}	stoichiometric coefficient of species i on the reaction j
ξ	mass conservation source term
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant
ψ	energy conservation source term
ω	angular velocity (rad/s)

Subscripts

CR	chemical reactions
CV	change of volume
ER	electrochemical reactions
F	forces
HT	heat transfer
int	interface
MT	mass transport
S	shaft work

ship machinery components. Next, a description of the individual component models is presented. Finally, the applicability and potential advantages of our marine energy systems modelling is illustrated via two case studies: the thermo-economic design and operation optimisation of a combined cycle system for large bulk carriers, and the transient operation simulation of an electric marine propulsion system.

2. Marine energy systems

The ship machinery system incorporates all onboard machinery that is used for propulsion, manoeuvring, cargo handling, fresh water production, heating, etc. This set of equipment constitutes the ship's energy conversion system, often referred to as the marine energy system. Marine energy systems convert the chemical energy of the fuel to those forms required shipboard and they tend to be highly complex, having many functions, with variable mission profiles, as well as requirements for flexibility, redundancy and safety, Fig. 1. The machinery-related operating costs often amount to 50–60% of the total ones [1], while at the same time, primary energy conversion is responsible for all gaseous emissions to air.

Compared to land-based energy systems, the marine ones have to be completely autonomous in terms of resources to be utilised for coverage of the demand. This is a key difference and source of additional complexity. Several constraints have to be met during their design and operation mandated from international regulations and design codes dealing with safety of life at sea [2], pollution prevention [3], and rules concerning the safety and availability of the main functions of the onboard machinery in order to maintain the essential services of the vessel [4]. The mission of the vessel and its operating profile are also highly variable depending on the trading route, weather conditions, and ship loading. Finally, the hull shape, arrangement and payload requirements impose additional constraints on the layout of the marine energy system in terms of location, volume, footprint, and weight.

To navigate through this complex landscape the design, operation and control of marine energy systems requires additional effort to produce solutions that are optimal from various points of view. The systems have to be:

- Flexible in operation to fulfil their time-varying mission.
- Energy efficient to minimise operational costs and weight of resources onboard.
- Of small emissions footprint to preserve the environment and satisfy international legislation.
- Reliable and redundant to minimise failures en-route and to satisfy numerous safety requirements.
- Easy to maintain to minimise downtime in sea or at port.
- Cost-effective to minimise the size of the investment.

To meet the aforementioned challenges a step beyond individual component modelling and simulation is required. There is a need for shifting the focus on the entire energy system performance and all complex interactions between individual components adopting a systems engineering philosophy.

3. Process modelling framework

3.1. Systems engineering in shipping

Systems Engineering (SE) is a methodological approach to the design, implementation and operation of complex technical systems. SE methodologies focus on the interactions of the constituents of the system, how they are interconnected, and what is their influence on the overall behaviour and/or performance of the