WEENTECH Proceedings in Energy

ICEEE 2016

16th -18th August 2016
Heriot-Watt University, Edinburgh
United Kingdom

Volume 3: International Conference on Energy, Environment and Economics, September 2016

ISSN: 2059-2353
ISBN: 978-9932795-2-2
www.weentech.co.uk

Edited by:
Dr. Renu Singh, IARI, New Delhi, India
Dr. Anil Kumar, PSU, Thailand
Published by World Energy and Environment Technology Ltd.

Numerical Studies of the Heat Transfer Performance of LNG Ambient Air Vaporizer under Frost Conditions

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Abstract

This paper reports a numerical heat transfer study of LNG ambient air vaporizer under frost conditions. The moist air around the AAV fin tube may freeze during the long-time operation, leading to a decrease of the heat transfer performance of AAV. The purpose of the study is to find out how the frost layer affect the heat transfer performance of the air side of the AAV. Based on the comparison between the frost growth model and frost structure model, a cryogenic frost formation model was proposed and solved. The results show how the thermal resistance of frost layer vary with time and atmospheric conditions. The heat transfer coefficient of the air side of the AAV fin tube under frost condition was calculated. The influence of the frost formation on the heat transfer performance of the fin tube was investigated.

Keywords: Liquefied natural gas; Ambient air vaporizer; Heat transfer; Frost formation;

1. Introduction

In recent years, liquefied natural gas (LNG) plays a more and more important role in gas usage system, due to its convenience in storage and transportation. However, LNG should be vaporized to natural gas in order to be transported to city gas pipeline. LNG vaporizer is a kind of heat exchanger used in many receiving terminals and gas stations.

LNG vaporizer can be classified to four categories according to the heat source: open rack vaporizer (ORV), ambient air vaporizer (AAV), submerged combustion vaporizer (SCV) and intermediate fluid vaporizer (IFV). The selection of the LNG vaporizer depends on the scale of the gas station, economics and climatic environment, etc.

AAV is widely used in small to medium gas stations due to its low cost in operating and eco-friendly advantages. The heat source of AAV is atmospheric air. It is composed of a group of parallel fin tubes. The common AAV type is 8 fins and 12 fins. Generally, LNG flows into the bottom of the AAV fin tube, through vaporization , and flows out the top of the tube in the form of natural gas. The outlet temperature of natural gas should meet the need of the gas pipeline.

However, the cryogenic LNG may cause the frost formation of the moist air around the AAV fin tube. The frost layer increases the thermal resistance and may block the air flow channel around the fin tube. This may lead to the incomplete vaporization of LNG and brings hazard in natural gas transportation. Therefore, studying the influence of the frost layer on the heat transfer performance of AAV is of vital importance.

Many researches about the frost formation on the heat exchanger have been done. Reid[1] investigated the frost mechanism on the cold surface using an experimental setup of liquid nitrogen cooling plane. The research shows that the density gradient of frost layer is small. Hayashi[2] used the microscope camera to observe the frost growth cycle on the cold surface and proposed a widely recognized three-stage growth theory. Schneider[3] investigated the changing rule of the frost layer thickness with different Reynolds number by experiment. The research shows that the air velocity has slightly influence on the frost growth. Miller[4] found out that the main influential factor of the frost formation on the heat pump fin tube heat exchanger is the thermal physical parameters of the atmospheric air. Ameen[5] studied how the frost formation on the heat exchanger affect the heat pump performance by experimental and theoretical methods.

It can be seen from the literatures that the study on frost formation is mainly applicable to cold surface. The temperature of the AAV fin tube is much lower and belongs to cryogenic surface. The frost formation process is quite different between cold and cryogenic surfaces, so many empirical correlations cannot be used in the cryogenic frost formation. This paper focuses on the frost formation on the cryogenic AAV fin tube surface and investigates the influence of the frost layer on the heat transfer efficiency.

2. Thermodynamic analysis

The frost formation mechanism was analyzed based on the phase diagram of water as Fig. 1 shows[6]. When the partial pressure of water vapor is less than 0.611kPa and its temperature is lower than the corresponding saturated temperature, the sublimation will occur directly. If the partial pressure of water vapor is higher than 0.611kPa and the temperature is lower than the freezing point, the water vapor will condense into water and then freeze into ice crystal.

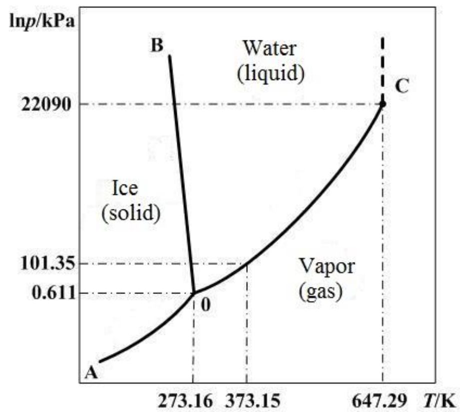

Fig. 1 The phase diagram of water

Based on the analysis above, the formation of the frost crystal can be divided into two basic types. One type is that the water vapor condenses into water drops firstly and then freezes into frost crystal. This type occurs when the temperature of water vapor is lower than the freezing point and the partial pressure is higher than the triple point. Another type is that the water vapor freezes into frost crystal directly. This type occurs when the partial pressure of water vapor is lower than 0.611kPa.

The temperature of the AAV fin tube outer surface ranges from 120K to 200K approximately, which is much lower than the triple point of water. However, the frost crystal may not occur if the partial pressure of water was not in the range. Furthermore, the continuous gathering of the frost crystal is essential to form frost layer. The concentration gradient of the water vapor between the atmospheric air and the moist air is the driving force. This means that only when the vapor concentration of the atmospheric air is higher than the moist air around the fin tube, the water vapor will spread to the cryogenic fin tube surface , which lead to the frost formation.

3. Mathematic model

The mathematic model of the frost formation on the cryogenic surface is based on the conservation of energy and mass, which is similar with the frost formation on the cold surface. However, the thermophysical parameters of the frost is quite different. Some assumptions were made to simplify the model: the thermophysical parameters of the frost is uniform at different thickness; the frost growth is one dimensional; the temperature of the cryogenic fin tube surface is time-invariant; the moist air on the cryogenic frost layer surface is saturated .

3.1 Mass conservation

According to the convective mass transfer, the water molecule passes from the air into the frost layer via the gas-solid interface.

$$\frac{dM_f}{d\tau} = h_m\left(\rho_{v,a} - \rho_{v,f}\right) \tag{1}$$

$$M_f = \delta_f \rho_f \tag{2}$$

The mass transfer coefficient h_m was obtained by the Chilton-Colburn analogy[7].

$$h_m = \frac{h_f}{\rho_a c_{p,a} Le^{\frac{2}{3}}} \tag{3}$$

The moist air was assumed to be ideal gas, so the density of the water vapor $\rho_{v,a}$ and $\rho_{v,f}$ can be calculated as

$$\rho_{v,a} = \frac{\varphi P_{sat,a}}{R_v T_a} \tag{4}$$

$$\rho_{v,f} = \frac{(1+s)P_{sat,f}}{R_v T_{sur}} \tag{5}$$

$$s = \frac{P - P_{sat}}{P_{sat}} \tag{6}$$

The mass conservation equation can be described as

$$\frac{d(\delta_f \rho_f)}{d\tau} = h_m\left(\rho_{v,a} - \rho_{v,f}\right) \tag{7}$$

3.2 Energy conservation

The total heat transfer rate can be written as

$$q = q_s + q_l \tag{8}$$

$$q_s = h_f (T_a - T_{sur}) \tag{9}$$

$$q_l = I_{sv} m_f \tag{10}$$

$$q = \lambda_f \frac{T_{sur} - T_w}{\delta_f} \tag{11}$$

The energy conservation equation can be described as

$$\lambda_f \frac{T_{sur} - T_w}{\delta_f} = h_f(T_a - T_{sur}) + I_{sv} m_f \quad (12)$$

3.3 Thermophysical parameters

In order to close the mass and energy conservation equations, the empirical correlations of the density and thermal conductivity of frost on the cryogenic surface were introduced based on the research of Auracher[8]. The frost layer is regarded as porous media composed of air and ice, so the thermal parameters of frost layer are affected by the structure.

$$\frac{1}{\lambda_f} = \frac{\zeta}{\lambda_{min}} + \frac{1-\zeta}{\lambda_{max}} \quad (13)$$

$$\lambda_{max} = (1-\psi)\lambda_{ice} + \psi\lambda_a \quad (14)$$

$$\frac{1}{\lambda_{min}} = (1-\psi)\lambda_{ice} + \frac{\psi}{\lambda_a} \quad (15)$$

$$\zeta = 0.42(0.1 + 0.995^{\rho_f}) \quad (16)$$

$$\rho_f = (1-\psi)\rho_{ice} + \psi\rho_a \quad (17)$$

$$\psi = 1 - 0.710 ex\,p[0.228(T_{sur} - 273.15)] \quad (18)$$

$$\lambda_{ice} = \frac{630}{T} \quad (19)$$

It's pretty hard to get the analytical solution of the equations, therefore Matlab was used to numerically solve the equations. The differential equations were discretized and the time step were revised repeatedly in order to obtain an accurate result.

4. Results and discussions

This paper aims to investigate the influence of the frost formation on the heat transfer performance of the AAV fin tube. The frost formation will increase the thermal resistance and reduce the heat transfer efficiency of AAV fin tube. By solving the cryogenic frost formation model, the frost thermal resistance and the heat transfer efficiency of the fin tube under frost conditions were investigated.

4.1 Frost thermal resistance

Fig. 1 shows the change of the frost thermal resistance with time. It can be seen that the thermal resistance increases with time overall. The thermal resistance increases rapidly at the beginning of the frost formation, and then increases slowly as time lasts. It is because that the frost layer thickness increases fast at the beginning of the frost formation and then becomes slowly as time goes. When the frost layer thickness grows to a certain extent, the frost density begins to increase instead of the thickness.

$$R_f = \frac{\delta_f}{\lambda_f} \quad (20)$$

To see the influence of the air temperature on the frost thermal resistance, numerical calculations on different air temperatures were carried out. Fig.2 shows how the frost thermal resistance changes with air temperature at different time. The thermal resistance increases with air temperature and then decreases, and the maximum value occurs at about -15℃. The low temperature and high temperature are equally bad for the frost growth. The mass transfer of the frost formation process is slow, which loose the frost layer. When the air temperature is high, the back melting and regrowth of the frost layer alternate quickly, leading to high frost density.

To investigate the effect of the air relative humidity on the thermal resistance, numerical calculations were carried out. Fig.3 shows the change of the thermal resistance with different air relative humidity. The change trend is similar to Fig.2, and the maximum value occurs at 30%. The thermal resistance ranges from 0.12~0.18(m^2·K/W), which means that the relative humidity of the air has little influence on the thermal resistance.

Fig.4 shows how the thermal resistance changes with different wall temperature. The thermal resistance decreases linearly as the wall temperature increases. There is no frost formation when the wall temperature is about 270K. The variation range of the thermal resistance with different wall temperature is wide.

It can be seen from the analysis of the influencing factors of the frost thermal resistance that the wall temperature is the largest influencing factor, second is the air temperature and the last is the relative humidity.

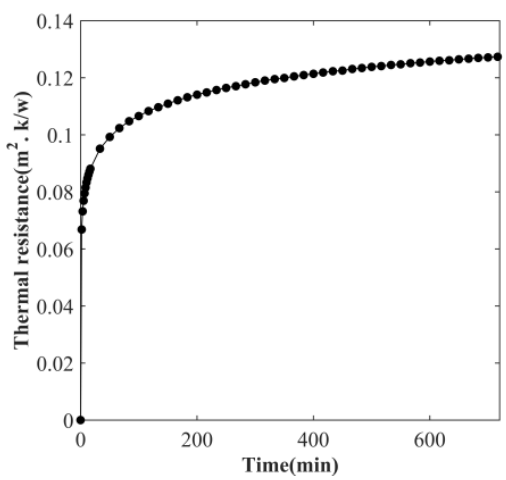

Fig. 1 The change of frost thermal resistance with time. $Ta = 30℃, \varphi = 50\%, T_w = 200K$

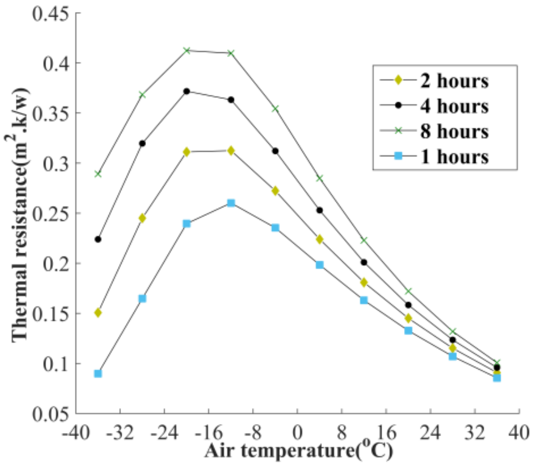

Fig. 2 The change of frost thermal resistance with different air temperature. $\varphi = 50\%, T_w = 200\text{K}$.

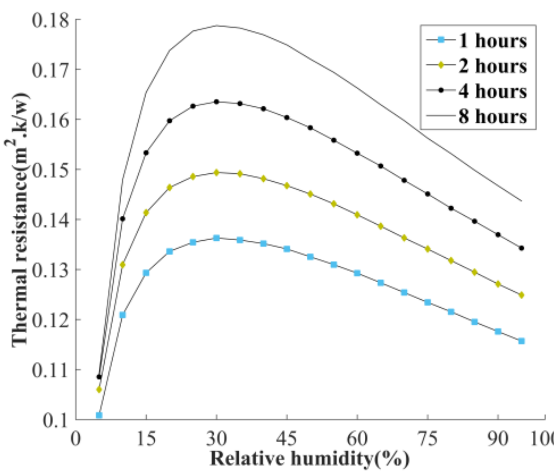

Fig. 3 The change of frost thermal resistance with different relative humidity. $Ta = 20℃, T_w = 200\text{K}$

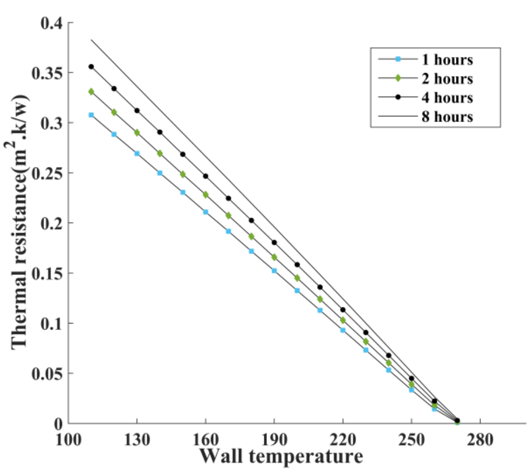

Fig. 4 The change of frost thermal resistance with different wall temperature. $Ta = 20℃, \varphi = 50\%$.

4.2 Heat transfer effect of frost formation

The combined heat transfer coefficient h_a between the fin tube surface and the atmospheric air involves the conduction of the frost layer, the natural convection between the frost layer and air, and the radiation. The effect of the frost formation on heat transfer is reflected in h_a. The air natural convection coefficient is calculated based on the correlation equations of the vertical wall. The radiation heat transfer is described by the surface coefficient of the radiation heat transfer.

$$Q = h_a(T_a - T_w)A_0 \tag{21}$$

$$h_a = \eta\beta h_o \tag{22}$$

The frost layer adds thermal conduction process to the surface heat transfer of the fins, which will affect the fin efficiency of the fin tube directly. The fin efficiency of a fin tube is constant without frost formation if the air temperature and the wall temperature did not change. However, the fin efficiency is changeable under frost condition as Fig. 5 shows. There is a positive correlation between the fin efficiency and the thermal resistance. It is because that frost thermal resistance decreases the heat transfer coefficient between the fin surface and air, thus reduces the temperature difference between the base tube and fin.

The increase in the fin efficiency does not means heat transfer enhancement. Frost layer has an effect of thermal insulation layer, which hinders the heat transfer between the fin surface and air. Fig. 6 shows that the surface heat transfer coefficient decreases as thermal resistance increases. In the liquid phase part of the AAV fin tube, the wall temperature is pretty low, resulting in high thermal resistance. In the extreme case, the heat transfer coefficient will reduce to 90%, which may brings vaporization failure.

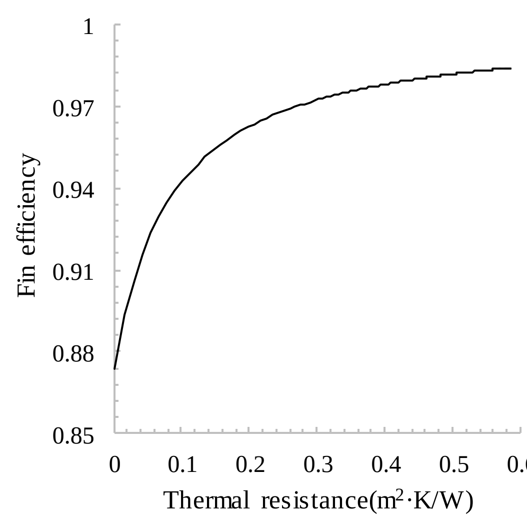

Fig. 5 The change of fin efficiency with thermal resistance. ($Ta = -15℃, \varphi = 30\%, T_w = 110\text{K}, H = 80\text{mm}$)

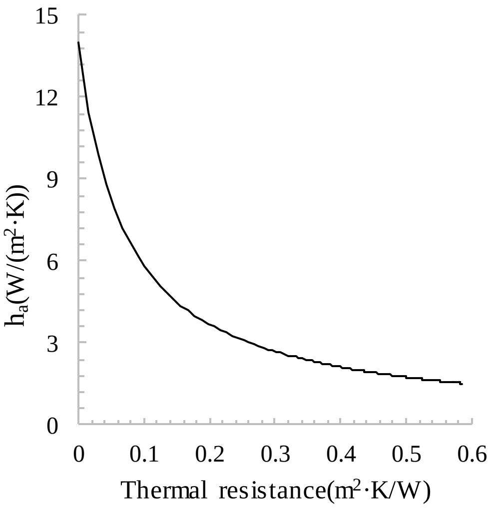

Fig. 6 The change of surface heat transfer coefficient of the fin with thermal resistance. ($Ta = -15$℃, $\varphi = 30\%$, $T_w = 110$K, $H = 80$mm)

5. Conclusions

A cryogenic frost formation model to investigate the influence of frost formation on heat transfer performance of fin tube has been presented. Based on the model, the frost thermal resistance and its influence on heat transfer coefficient were studied. The following conclusions can be made.

(a) The thermal resistance increases rapidly at the beginning of the frost formation, and then increases slowly as time lasts.

(b) The thermal resistance increases with air temperature and then decreases, as well as the relative humidity.

(c) Wall temperature is the largest influencing factor for frost thermal resistance.

(d) Frost thermal resistance decreases the surface heat transfer coefficient of fin tube.

Abbreviations

Liquefied Natural Gas (LNG)
Ambient Air Vaporizer (AAV)
Open Rack Vaporizer (ORV)
Submerged Combustion Vaporizer (SCV)
Intermediate Fluid Vaporizer (IFV)

Nomenclature

M_f mass per square meter (kg/m^2)
h_m interfacial mass transfer coefficient
$\boldsymbol{h_f}$ heat transfer coefficient (W/(m^2·K))
$\rho_{v,a}$ density of water vapour of the atmospheric air (kg/m^3)
$\rho_{v,f}$ density of water vapour of the frost surface (kg/m^3)
$\boldsymbol{\rho_f}$ density of the frost (kg/m^3)
$\boldsymbol{\rho_a}$ density of the atmospheric air (kg/m^3)
$\boldsymbol{\delta_f}$ thickness of the frost (m)
$\boldsymbol{c_{p,a}}$ specific heat of air at constant pressure (J/(kg·K))
$\boldsymbol{Le}$ Lewis number
$\boldsymbol{\varphi}$ relative humidity (%)
$\boldsymbol{P_{sat,a}}$ saturation pressure of water vapour at atmospheric temperature (kPa)
$\boldsymbol{P_{sat,f}}$ saturation pressure of water vapour of frost surface
$\boldsymbol{R_v}$ universal gas constant of the water vapour (J/(mol·K))
$\boldsymbol{T_a}$ atmospheric air temperature (K)
$\boldsymbol{T_{sur}}$ temperature of frost surface (K)
$\boldsymbol{T_w}$ wall temperature(K)
$\boldsymbol{s}$ super saturation degree (K)
$\boldsymbol{q_s}$ sensible heat flow (W/m^2)
$\boldsymbol{q_l}$ latent heat flow (W/m^2)
$\boldsymbol{I_{sv}}$ latent heat of sublimation of water vapor (kJ/kg)
$\boldsymbol{m_f}$ mass flux of the water vapor through the frost surface (kg/(m^2·s))
$\boldsymbol{\lambda_f}$ thermal conductivity of the frost (W/(m·K))
$\boldsymbol{\psi}$ frost porosity
$\boldsymbol{\lambda_{ice}}$ thermal conductivity of ice (W/(m·K))
$\boldsymbol{\lambda_a}$ thermal conductivity of air (W/(m·K))
$\boldsymbol{\rho_{ice}}$ density of ice (kg/m^3)
$\boldsymbol{h_o}$ the air natural convection coefficient(W/(m^2·K))
$\boldsymbol{A_0}$ the standard area of the out surface of fin tube(m^2)
$\boldsymbol{\eta}$ the overall efficiency of the fin tube
$\boldsymbol{\beta}$ finned coefficient
H height of the fin(mm)

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Commonwealth Energy and Sustainable Development Network (CESD-Net)

CESD-Net is a major global initiative in energy and sustainable development. The objective of network is to promote energy and sustainable development in commonwealth countries.

Focussing on Multidisciplinary Research, Promoting Future Low Carbon Innovations, Transferring Knowledge and Stimulating Networking among Stakeholders to Ensure the UK Achieves World Leading Status in Energy and Sustainable Development. https://www.weentech.co.uk/cesd-net/

The 1st International Conference on Energy, Environment and Economics (ICEEE 2016) was held at Heriot-Watt University, Edinburgh, EH14 4AS, UK, 16-18 August 2016. ICEEE2016 focused on energy, environment and economics of energy systems and their applications. More than fifty eight delegates from 31 countries with diverse expertise ranging from energy economics, solar thermal, water engineering, automotive, energy, economics and policy, sustainable development, bio fuels, Nano technologies, climate change, life cycle analysis etc. made conference true to its name and completely international. During conference total 51 oral presentations and six posters were shared between delegates. The presentations showed the depth and breadth of research across different research areas ranging from diverse background. ICEEE2016 aimed:

- To identify and share experiences, challenges and technical expertise on how to tackle growing energy use and greenhouse gas emissions and how to promote sustainability and economical, cost effective energy efficiency measures.

In total 11 technical sessions and two invited talks both from academia and industry provided insight into the recent development on the proposed theme of the conference. Preparation, organisation and delivery of the conference started from July 2015 and further co-ordinated by vibrant team of Conference Centre, Heriot Watt University. Conference organisers would like to acknowledge support from the sponsors particularly World Scientific Publication ltd and its team members for the delivery of the conference. Organisers are also thankful to all reviewers who contributed during peer review process and their contributions are well appreciated. At the end and during vote of thanks following awards have been announced and we would like to congratulate all well deserving delegates.

- Best Paper –Academia: Amela Ajanovic, EEG, TU Vienna, Austria
- Best Paper – Student : Christian Jenne,University of Duisburg-Essen, Germany
- Best Poster – Student: Yoann Guinard, University of New South Wales, Sydney, Australia
- Best Poster – Academia: E. Salleh, Universiti Kebangsaan Malaysia, Malaysia
- Active Participation Award - Yoann Guinard, University of New South Wales, Sydney, Australia

At the end we would like to extend our gratitude to all of you for your participation and hopefully welcome you again during ICEEE2017.

Editors:

Dr. Singh is Senior Scientist at Indian Agricultural Research Institute, New Delhi, India. Her area of expertise are bio energy and bio fuels, environmental engineering, carbon accounting and renewable energy integration for rural development.

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WEENTECH Proceedings in Energy- International Conference on Energy, Environment and Economics, September 2016

Edited by:

Dr. Renu Singh, IARI, New Delhi, India

Dr. Anil Kumar, PSU, Thailand

Publisher: World Energy and Environment Technology Ltd., Coventry, United Kingdom

Publication date: 12 September 2016

ISSN: 2059-2353

ISBN: 978-9932795-2-2

To purchase e-book online visit www.weentech.co.uk or email conference@weentech.co.uk