International Institute for
Carbon-Neutral Energy Research

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Thermal Science & Engineering Revised Roadmap

January 2019

KYUSHU UNIVERSITY

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Division Objective

- **Expand material thermophysical property information and thermal science and engineering to help enable the most effective use of materials in carbon-neutral energy society technologies and to improve the energy efficiency of thermal processes.**

  - Expand our knowledge base of the thermophysical properties of hydrogen and alternative refrigerants to enable their most efficient use to reduce CO_2 emissions.
  - Improve the understanding of the basic science of heat and mass transfer to enable the develop of more efficient energy and power generation systems.
  - Research new thermal energy heat pump and refrigeration systems focused on the use of waste heat and new refrigerants resulting in improved overall energy efficiencies and reduced CO_2 emissions.

Division Projects, Objectives, and Research Efforts (1)

	Projects	Objectives	Research Efforts	Researchers
Area1: Thermophysical properties (TP)	**TP-1:** High Pressure Hydrogen	Measurement of thermophysical properties of hydrogen and development of its database in a wide range of temperatures and pressures needed <u>for hydrogen energy system</u>	･Accurate measurement of PVT relationship, viscosity, thermal conductivity, velocity of sound ･Study on rigorous heat transfer characteristics	Y. Takata ○ N. Sakoda
	TP-2: Next generation refrigerants (NEXT-RP)	Measurement of thermodynamic properties of newly developed environmentally-friendly refrigerants that are candidates <u>for next generation air-conditioning systems</u>	･Measurement of thermodynamic properties and critical point ･Accurate measurement of PVT relationship and development of thermophysical properties database ･Development of a new equation of state (EOS)	Y. Takata ○Y. Higashi N. Sakoda B.B. Saha K. Thu
	TP-3: Thermal transport in nanoscale	Elucidation of thermal transport of nano materials and interfaces <u>for various energy devices (e.g. adsorbent of adsorption heat pump/refrigeration system).</u>	･Measurement of thermal conductivity of nanowires ･Development of new measurement methods of thermal/electrical/optical properties of nano materials	○K. Takahashi X. Zhang M. Kohno N. Miljkovic H. Sivasankaran Q. Li

Division Projects, Objectives, and Research Efforts (2)

Projects		Objectives	Research Efforts	Researchers
Area 2 : Heat/Mass Transfer (HMT)	**HMT-1:** Phase change heat transfer	Elucidation of effect of surface wettability and structure on liquid-vapor phase change process for effective heat removal for high-heat flux conditions	･Mechanism of bubble nucleation and condensation in nanoscale observation by TEM, AFM and FIB-ESEM ･Elucidation of heat transfer characteristics by pool boiling and droplet impingement for various wettability surfaces including loop heat pipes ･Mechanism of liquid drop evaporation on heated substrate ･Condensation heat transfer from nano- to macroscale ･bio-mimetic surface	○Y. Takata K. Takahashi M. Kohno K. Sefiane ~~D. Orejon~~ B. Shen N. Miljkovic H. Sivasankaran Y. Kita
	HMT-2: Adsorption	Characterization of functional adsorbents and measurement of adsorption isotherms & kinetics for adsorption heat pump/refrigeration system/thermal energy storage	･Synthesis of activated carbon-based composite adsorbent ･Measurement of adsorption characteristics in a wide range of temperature and pressure ･HMT analysis of adsorbent bed ･Evaluation of thermodynamic models for adsorbed phase	○B.B. Saha T. Miyazaki K. Thu J. Miyawaki ~~K. Uddin~~

Division Projects, Objectives, and Research Efforts (3)

	Projects	Objectives	Research Efforts	Researchers
Area 3：Thermal Energy Systems (TES)	**TES-1:** Waste heat-driven adsorption heat pump/ refrigeration system	Development of adsorption heat pump/refrigeration and energy storage systems for utilization of 50-200°C level waste heat Development of ultra efficient hybrid heat pump and power cycles	･System analysis of adsorption thermodynamic cycles ･Development of compact adsorption heat exchangers ･Theoretical and simulation of hybrid heat pump cycles ･Second law analysis of hybrid heat pump and power cycles	○B.B. Saha T. Miyazaki K. Thu ~~K. Uddin~~
	TES-2: Vapor compression heat pump/ refrigeration system using new refrigerants (NEXT-RP)	Development of heat pump/refrigeration system using low GWP refrigerants and their mixtures with high COP	･Optimization of thermo-dynamic cycle using thermo-physical property data ･Design and optimization of evaporator and condenser ･Entropy/exergy analyses of heat pump/refrigeration systems	○ Y. Higashi B.B. Saha T. Miyazaki K. Thu Y. Takata N. Sakoda ~~K. Uddin~~
	TES-3: High Efficiency Power Generation System	Development of highly efficient coal/biomass (w/solar thermal assist) power generation systems to produce H_2 with CCS (imported low CO_2/CO_2 free H_2). H_2 oxy-fuel combustion cycles using cold energy of liquid H_2 for air separation unit	･Thermodynamic cycle analysis considering chemical reactions ･Modeling and numerical simulation of turbulent combustion process	H. Watanabe ○Y. Takata A. Yamada

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Milestones (1)

	2018-2020 (short)	2021-2030 (mid)	2031-2050 (long)
TP-1: High Pressure Hydrogen (Completed)	Establishment of prediction method for hydrogen permeation through metal wall Accurate prediction of transient pressure and temperature behaviors in H_2 refueling process **(Accomplished)**	Development of technique for accurate prediction of heat and fluid flow Establishment of technique for accurate measurement of thermal properties **(Accomplished)**	

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Milestones (2)

	2018-2020 (short)	2021-2030 (mid)	2031-2050 (long)
TP-2: New refrigerants	PVT measurements of newly synthesized refrigerants, their mixtures, and development of their accurate EOS **(Accomplished)**	Development of thermophysical property database for new refrigerants and their mixtures; Compilation of thermophysical property data for various new refrigerants	
TP-3: Thermal transport in nanoscale	Development of experimental techniques for interfacial thermal transport	Clear understanding of nanoscale and interfacial thermal transport; Understanding of multiscale thermal transport in energy devices	

Milestones (3)

	2018-2020 (short)	2021-2030 (mid)	2031-2050 (long)
HMT-1: Phase change heat transfer	Development of boiling surface with onset of boiling at less than 2K in ΔT_{sat} and with CHF by 2.5 times higher than copper surface Clear understanding of wettability effects in liquid-vapor phase change	Measurement of heat transfer characteristics of micro liquid layer in boiling and evaporation process by making use of thermoreflectance method Clear understanding of heat transfer performance and pressure drop of new refrigerants in evaporator and condenser Extension of wettability effects in boiling heat transfer to low surface tension liquids	Clear Understanding of liquid-vapor heat transfer from nano to macro scale
HMT-2: Adsorption	Accumulation of adsorption isotherm and kinetics data of natural or low GWP refrigerant onto functional adsorbents Clear understanding of adsorption/desorption process of functional adsorbents	Atomic scale understanding of adsorption phenomena for functional adsorbents Establishment of adsorption kinetic enhancement technique Adsorbed phase thermodynamics	Development of HMT enhancement technique for adsorption heat exchanger

Milestones (4)

	2018-2020 (short)	2021-2030 (mid)	2031-2050 (long)
TES-1: Waste heat-driven adsorption heat pump/ refrigeration system	Clarification of the best suitable adsorbent and refrigerant combination for adsorption heat pump and refrigeration systems	Demonstration of systems and optimization of operating conditions Second law-based optimization of hybrid heat pump and power cycles	Development of rapid adsorption/desorption heat exchanger using functional adsorbents
TES-2: Vapor compression heat pump/ refrigeration system using new refrigerants	Development of heat pump system for a wide range of temperature using new HFO and HFO blend refrigerants	Design criteria and performance prediction technique for heat pump/refrigeration with new refrigerants Entropy and exergy analyses	Development of prototype heat pump system with ultimate COP

Milestones (5)

	2018-2020 (short)	2021-2030 (mid)	2031-2050 (long)
TES-3: High Efficiency Power Generation System	Conceptual design of power generation system with high efficiency and zero/negative ~~low~~ CO_2 emission using coal/biomass and imported low carbon/carbon free H_2	Development of elementary processes and units including ~~combustor, reductor and gas separator~~ solar thermal assisted gasification and H_2 combustion turbines/ Numerical simulation technique for turbulent combustion process	Pilot plant of power generation system (1 MWt capacity)
	Understanding of turbulent-chemistry interaction in turbulent reacting flows by experimental and numerical examination Development of basic database for modeling Development of turbulent combustion models and validation on a fundamental configuration (DNS, LES)	LES modeling and simulation of turbulent combustion in turbulent reacting flows and validation on a larger scale problem Multi-physics modeling on interaction of fluid-structure Massively parallel computing on a large-scale target to confirm applicability to a practical scale problem	Multi-physics simulation on interaction of fluid-structure Massively parallel computing on a practical-scale problem to directly contribute to industries

Ultimate Targets (1)

		Ultimate targets	Current Benchmarks	Technology/Application
Area1: Thermophysical properties (TP)	**TP-1:** High Pressure Hydrogen (Complete)	• Clear understanding of thermophysical properties of hydrogen at low temperatures down to -30 °C and at high-pressure pressures up to 100 MPa with an accuracy of ±2% • Accurate prediction of heat and fluid flow of high-pressure hydrogen.	• Thermal conductivity and viscosity at -30 °C and up to 100 MPa by HYDROGENIUS • Development of a simulation software to predict the state change of high-pressure hydrogen for hydrogen refueling stations (HRS) by HYDROGENIUS	• Hydrogen property data base and HRS dynamic simulation for hydrogen station and infrastructure • Basic science underpinnings/properties database complete – transitioning to applications (in collaboration with government and industry)
	TP-2: New refrigerants	• Development of equation of state for new HFO refrigerants and their mixtures • Elucidation of heat transfer characteristics for new HFO refrigerants and their mixtures	• PVT, critical point and vapor pressure of HFO refrigerants by Higashi et al.	• Vapor compression heat pump/ refrigeration system (contribute to TES-2)
	TP-3: Thermal transport in nanoscale	• Multiscale analysis of thermal transport in and around nanomaterials • Elucidation of thermal transport at complex interfaces	• Measurement of thermal conductivity of carbon nanotube(CNT) by T-junction technique by Zhang, Takahashi and Fujii. • Measurement of heat conduction at simple interface by TDTR method developed by Cahill	• High efficient thermal transport device

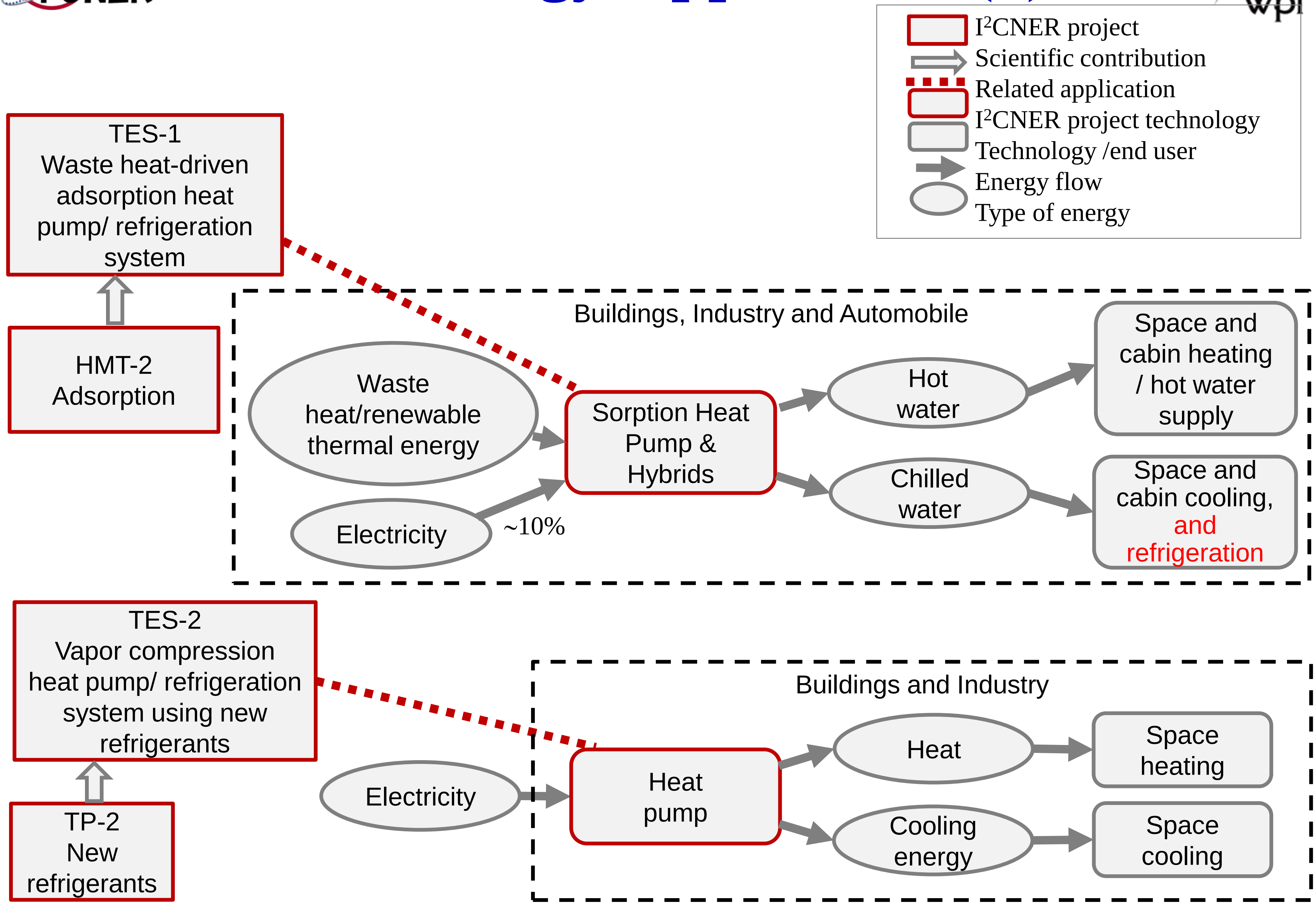
Ultimate Targets (2)

		Ultimate targets	Current Benchmarks	Technology/Application
Area 2 : Heat/Mass Transfer (HMT)	**HMT-1:** Phase change heat transfer	• Elucidation of wettability and structure effects in liquid-vapor phase change phenomena	• Mixed-wettability boiling surface by Takata et al.	• Loop heat pipe (i.e. for data center) • Power device cooling (i.e. inverter)
	HMT-2: Adsorption	• Cooling capacity per adsorbent bed: 1.5 kW/L, for example, ethanol-activated carbon system: (Specific cooling effect 900 kJ/kg x packing density 0.3 kg/L)/(adsorption time 180s) • Thermodynamic models and data for adsorbed phase (u, h, s, c_p, c_v etc.)	• AQSOA®-Water system: 0.5 kW/L by Mitsubishi Plastics • No data on the adsorbed phase thermodynamic properties	• Waste heat-driven adsorption heat pump/ refrigeration system • Hybrid cycle heat pump system using vapor compression and waste heat (contribute to TES-1)
Area 3 : Thermal Energy Systems (TES)	**TES-1:** Waste heat-driven adsorption heat pump/ refrigeration system	• HP systems with large specific heating/refrigeration power • Raise COP toward 0.9 at heat source temperature level of 80℃ • Hybrid cycle with COP higher than vapor compression cycles	• COP 0.6@60℃ by Maekawa MFG (adsorption heat pump) • About 6.5 COP at compressor level (mechanical heat pump)	• Waste heat-driven adsorption heat pump/ refrigeration system • Hybrid cycle heat pump system using vapor compression and waste heat
	TES-2: Vapor compression heat pump/ refrigeration system using new refrigerants	• COP 10 on the basis of electricity input using non-GWP refrigerant • Performance enhancement using entropy- and exergy-based system analyses	• COP 6.5 on the basis of electricity input ~~primary energy~~ by air-conditioning/refrigeration makers	• Vapor compression heat pump/ refrigeration system
	TES-3: High efficiency power generation system	• Thermal efficiency and CO_2 emission 65%/~~300g~~-zero/negative CO_2/kWh	• Thermal efficiency and CO_2 emission • OxyFuel: 30%/90g-CO_2/kWh ~~IGCC:40%/700g-CO_2/kWh~~	• High efficiency power generation system using coal and imported low carbon H_2

Role & Contribution through Technology

- The role of this division toward CNS is to create
  1. Heat and mass transfer devices to reduce energy loss in heat transfer in the applicable field such as data centers, contributing to energy saving for air conditioning
  2. Efficient waste heat / renewable thermal energy driven heat pump, contributing to efficiency increase and energy saving for heating and cooling applications where waste heat / renewable thermal energy air are available such as factory and automobile
  3. High efficiency vapor compression heat pump, contributing to efficiency increase and energy saving for air conditioning in all sectors

Technology/Application (1)



Technology/Application (2)