High Temperature Heat Exchanger Project

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UNLV Research Foundation
High Temperature Heat Exchanger (HTHX) Project
Quarterly Report

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Summary

Program Management

- **HTHX Kickoff Meeting**

    - On October 24, 2003, the University of Nevada, Las Vegas (UNLV) hosted an all-day HTHX Kickoff Meeting attended by all participating institutional representatives and researchers. Objectives of this meeting were to identify near-term research objectives, coordinate collaborative activities, and identify required urgent action items. A number of important items resulted in actions reported below.

    - An HTHX Website was created on the UNLV Harry Reid Center server to provide important information to project participants. Information that is not releasable to the general public is protected by a password for collaborators to access. The website is located at http://nstg.nevada.edu/heatexchangers.html The website will archive all presentations and handouts from HTHX Project meetings and other relevant information.

    - Significant changes in project scope required re-writing the Scope of Work approved for General Atomics Corporation (GA). Specifically, all references to Intermediate Heat Exchanger (IHX) work was removed, and other important tasks for GA were identified, as detailed below.

    - Additionally, the participants concluded that the project would benefit significantly from the establishment of a Materials Selection Advisory Committee (MSAC) to assist in identifying and prioritizing selection of candidate materials for characterization and testing. It is expected that MSAC contributions will prevent redundancy and promote efficiency by coordination with the related national program including the IHX.

    - Recommendations for the Materials Selection Advisory Committee have been provided by Tony Hechanova, Per Peterson, and Ron Ballinger.
        - Ceramics: Russ Jones (PNNL) and Dane Williams (ORNL)
        - Codes and Standards: TBD
        - Superalloys and Corrosion: Ron Ballinger (MIT) and Aziz Asphahani (Carus Chemical Co.)
        - Chemical Engineering: Jeff Tester (MIT)

        - Environmental Degradation: TBD (need someone who knows both the corrosion and the metallurgy sides)
        - HTHX Project Representatives: Ron Ballinger, Anthony Hechanova, Per Peterson, and Ajit Roy

    - The UC Berkeley (UCB) concept, a liquid-silicon-impregnated carbon-carbon composite, was approved for implementation and the UNLV Design and Testing group agreed to provide modeling support. Peterson [1] summarized the development of liquid-silicon-impregnated C/C-SiC composites for high-temperature heat transport. The UCB concept will use melt-infiltrated carbon-carbon composites to fabricate compact heat exchangers for the NGNP intermediate loop. These heat exchangers will use CVI carbon coating on the interior heat transfer surfaces, using a method developed at ORNL for coating carbon-carbon composite fuel cell plates. It is anticipated that molten-salt corrosion will not be a significant design issue for these heat exchangers. Likewise, these composite materials maintain full mechanical strength and are not subject to creep in the temperature range of interest for thermo-chemical hydrogen production. Significant progress has been made in mechanical and thermal design for these heat exchangers. However, resistance to helium permeation, materials compatibility with molten salts, and ASME code certification must be demonstrated before these materials could be qualified for commercial use.

- **Subcontract issues**

    - Subcontract issues raised by GA and UCB regarding standard indemnification language as well as other flow-down clauses are being discussed. UNLVRF awarded a subcontract to UCB, and negotiations with GA are underway to reach accord on indemnification language.

    - The GA scope of work included significant effort addressing the IHX that was subsequently determined to be outside the scope of this project. Accordingly, modifications to the GA work scope were made that
        - Removes all reference to IHX work
        - Requires additional work in Materials Characterization and Testing to provide corrosion testing of candidate materials in hot hydrogen iodide (HI) environments

      The modified GA Scope of Work was appended to the November progress report.

    - The GA effort to specify HTHX applications parameter range experienced difficulties in getting underway. In early January, the GA team for HTHX applications was assembled and firm deliverable products documented, as reported in the December progress report.

- **Reporting issues**

    - Someinitial confusion regarding financial and administrative reporting roles and responsibilities resulted from the manner in which the project was awarded by the Department of Energy. These issues have been clarified.

    - The DOE Contracting Officer, located in Albuquerque, reported that the responsibility for contract administration was being transferred to DOE's Idaho Operations Office.. However, the responsible individual in Idaho has not yet been identified.

<u>HTHX Design Studies-Highlights</u>

- **Objectives and scope**

    - Work with the U.S. Department of Energy Office of Nuclear Energy, Science and Technology (DOE NE) nuclear hydrogen research and development program elements on high temperature systems studies for hydrogen production.

    - Identify the range of HTHX applications for Gen IV hydrogen production.

    - Develop thermal systems concepts/designs and overall heat/mass balances for the range of Gen IV power conversion and hydrogen production concepts.

    - Develop design specifications for an intermediate-loop heat exchanger and other HTHXs used in the conceptual designs.

    - Undertake thermal hydraulic systems numerical modeling to establish and analyze temperature, pressure, and flow rate requirements.

    - Perform thermal, thermal-hydraulic, and structural analyses for selected advanced HTHX concepts for hydrogen production

    - Deliver detailed design for candidate intermediate heat exchanger concepts and materials for hydrogen production requirements.

- **HTHX applications parameter range**

    - No progress other than team identification and description of deliverable products reported.

- **HTHX design requirements and specifications**

    - A significant effort is proceeding in surveying the literature related to this and other milestone efforts. The documents reviewed are listed at the end of this report.

- **Thermal systems concepts and preliminary designs**

    - Hydrogen plant safety will be an important feature in HTHX designs, especially in light of the plant's proximity to a nuclear power source. High pressure helium, the primary competitor for molten salts for the intermediate fluid, creates a large stored energy source in the plant unless tertiary heat exchangers are used.

    - UCB wrote a report [2] summarizing the comparison of molten salt and high-pressure helium as the NGNP intermediate heat transfer fluid (Per F. Peterson, H. Zhao, and G. Fukuda, Comparison of Molten Salt and High-Pressure Helium for the NGNP Intermediate Heat Transfer Fluid, U.C. Berkeley Report UCBTH-03-004). UCB found substantial differences and tradeoffs between molten salts and high-pressure helium for use in an intermediate loop. Avoiding the risks of high pressure helium by molten fluoride salts incurs risks of explosive energy release if high volatility liquids contact the salt. Also, fluoride salts can react with sulfuric acid to release HF, which is quite toxic.

    - The potential for steam explosions and toxic gas production may mandate use of tertiary heat transfer fluids. The report concludes that the use of either thermal carrier incurs technical risks, and that both should be retained and studied until these technical issues are resolved and an optimal choice can be made.

    - Molten salt literature review and coordination with Oak Ridge National Laboratory (ORNL) staff resulted in preferential choice of zirconium-based salts (Zr-Na-Li) rather than flinak (Li-Na-K) or fluoroborate salts. Flinak salt and Zr-Na-Li salt were compared for intermediate HXs. Analysis showed that the effect of salt type on heat exchanger performance is small.

    - UCB considered tertiary loop HXs by considering a 10-bar, 30 MW(t) heat exchanger for transferring heat from molten salt to tertiary helium, where the helium pressure would be in balance with likely S-I process fluid pressures. UCB found that a good tertiary loop MS to helium IHX can be realized.

- **Thermal systems modeling**

  - For the heat exchanger thermal performance comparison, UCB identified the importance of the log-mean temperature difference (LMTD). Smaller values of LMTD are desirable to increase the temperature at which heat is delivered to the hydrogen production process and/or to decrease the peak temperature of the reactor while maintaining the same hydrogen production efficiency. In compact helium heat exchangers, a strong competition exists between adding surface area to decrease the LMTD and reducing surface area to reduce the helium pressure drop. Pressure drop and pumping power considerations usually drive helium heat exchangers to higher LMTD values than would be selected for molten salt heat exchangers.

  - The UCB compact plate fin HXs design Mathcad program was further developed by including LMTD as a parameter to facilitate the calculation. Calculation showed that a He-to-MS HX has a LMTD less than half of the LMTD for a He-to-He HX, for the same pumping power and a similar HX volume (and, approximately, capital cost).

  - The UNLV team, with the help of UCB team, obtained the thermo-physical properties of heat exchanger working fluids. Boundary conditions and operating conditions were also obtained from other external resources.

  - In November, a two-dimensional geometry was created using GAMBIT that will be used to perform calculations in the near term before adding the complexity of a third dimension.

  - In December, a two-dimensional hydrodynamic model of an offset strip fin heat exchanger was implemented. The model is being developed by UNLV using GAMBIT for mesh generation. The generated mesh is exported to FLUENT (a CFD code). Sample calculations were reported by Sundaresan Subramanian, a UNLV graduate student, in the December progress report. This work is included later in this report.

HTHX Design Studies-Technical Summary

At the October 24, 2003 HTHX Kickoff Meeting, it was decided that much of the research needs still need to be determined and that a working group should be convened to define the baseline HTHX concept and another working group to provide recommendations on materials selection. However, one research task was given the green light: the UCB concept. UCB's research plan was essentially approved and the UNLV Design and Testing Group agreed to support their concept through modeling.

Some general guidelines for the design team to consider are the following:

- Candidate working fluids for the HTHX needs to be given due consideration like molten fluoride salts, helium gas and S-I process fluids;
- Thermo physical properties of the fluids are very important;
- Proper flow channels need to be designed;
- Best heat transfer enhancement method should be chosen;
- Turbulence at high temperature such as 1000°C needs to be handled properly;
- Pressure loss should be reduced; and
- Leak tightness should be ensured.

The UCB design deals with a staggered or offset strip fin type of heat exchanger. The working fluids are helium gas and molten salt. The UNLV team will investigate heat transfer enhancement and geometry optimization to address the above issues. The thermal hydraulic conditions as temperature and flow rates will be calculated using computational methods. An initial step included obtaining thermo physical properties of materials and working fluids and correlations for heat transfer and pressure drop.

A working group is to be convened that includes collaborators from UNLV, Sandia, GA, ORNL and INEEL and possibly elsewhere to accumulate experience in HTHX engineering to down select and focus direction on the HTHX research for the UNLV Design and Testing team.

In discussions between Ron Ballinger, Tony Hechanova, and Per Peterson, the role and composition of the Materials Selection Advisory Committee was discussed. The main role of the advisory committee is to provide the best possible expert advice, not to serve as in an independent peer review capacity. The most important thing is to make sure that the committee has extensive background in the areas of expertise that the HTHX project needs in order to assure that we do not reinvent any wheels and that we do identify the best paths forward. Therefore, a perceived conflict-of-interest is a not major issue. Advisory Committee recommendations were provided as follows:

- Ceramics: Russ Jones (PNNL) (first choice, he spoke to Tony Hechanova on Dec. 3 2003 and expressed his interest) and Dane Williams (ORNL). Russ is more involved with actual research
- Codes and Standards: no one yet identified
- Superalloys and Corrosion: Ron Ballinger (MIT) and Aziz Asphahani (Carus Chemical Co.)
- Chemical Engineering: Jeff Tester (MIT) (a good hydrogen guy as well)
- Environmental Degradation: need someone who knows both the corrosion and the metallurgy sides
- HTHX Project Representatives: Ron Ballinger, Anthony Hechanova, Per Peterson, and Ajit Roy

Model Development

Prandtl numbers for the fluids of coolant candidates have been calculated using references provided by the UCB team. Material properties were provided by the UCB team and are given in Tables 1 and 2. These values will be used for input in the material properties section during CFD modeling using FLUENT. The most suitable heat transfer correlations are being studied for our application.

Table 1. Fluid material properties (700 ^oC)

Material	ρ (Kg/m^3)	Cp (J/kg K)	K (W/m K)	Prandtl Number	$\mu \times 10^{-3}$ (Kg/m-s)
$^7Li_2BeF_4$ (Flibe)	1940	2340	1.1	13.1508	5.62
$0.58NaF\text{-}.42ZrF_4$	3140	1170	2.1	0.927	1.664
$0.42LiF\text{-}.29NaF\text{-}0.29ZrF_4$	2706	1470	2.1	3.101	4.434
Helium (7.5 MPa)	3.8	5200	0.29	0.749	0.0418

Table 2. Solid material properties (700 ^oC)

Material	ρ (Kg/m^3)	Cp (J/kg K)	K (W/m K)
Liquid silicon impregnated carbon composites	2000	1200	20

The commercial CFD software FLUENT has been used for heat exchanger flow modeling. Initially a 2-D mesh was created using GAMBIT with the geometry specifications as provided by the UC Berkeley team. The Reynolds number of flow modeling is 2128.

Mesh was created using triangular mesh with pave as default and spacing 0.2.

The following is the summary of the boundary condition used in GAMBIT:

- Channel Walls: edge 1 and 3;
- Periodic Boundaries: edge 2 and 4; and
- Fin walls: the fin edges.

The generated computational mesh was exported to FLUENT. Many different boundary condition types have been studied. Channel walls with no-slip condition and periodic boundaries are used.

The periodic boundary option was chosen for the inlet and outlet because the helium velocity is not going to be the same all the way through the channel. The computational domain is going to be repeated all through the channels, i.e., fin placing is similar all through from inlet to exit zone.

For input of the values in laminar flow, segregated solver and 2-D was used. Initially, heat transfer was not considered, only the fluid flow alone was considered. Therefore, the energy equation was not chosen at the beginning of simulation.

Helium was considered for the fluid side and the solid material was composites; the respective values for their thermal physical properties were entered. The channel walls were assumed to have no-slip boundaries.

After setting all boundary conditions, the PERIODIC BOUNDARY mass flow option was chosen as the UCB team has specified the mass flow rate of helium in a single channel as 26.136 kg/s. FLUENT iterates the pressure gradient as per the desired mass flow rate.

Initialization was done first from all zones with specified helium X-Velocity as 17 m/s and the contours were compared with those when no velocity was specified. The resulting velocity contours were similar, as shown in figures below.

However, using channel walls with no-slip boundaries might not be a proper approach as in real-time application our HX will have fluid flowing in adjacent walls and more investigation needs to be done in this issue.

The 2-D Mesh that is used as the computational domain is shown in Figure 1.

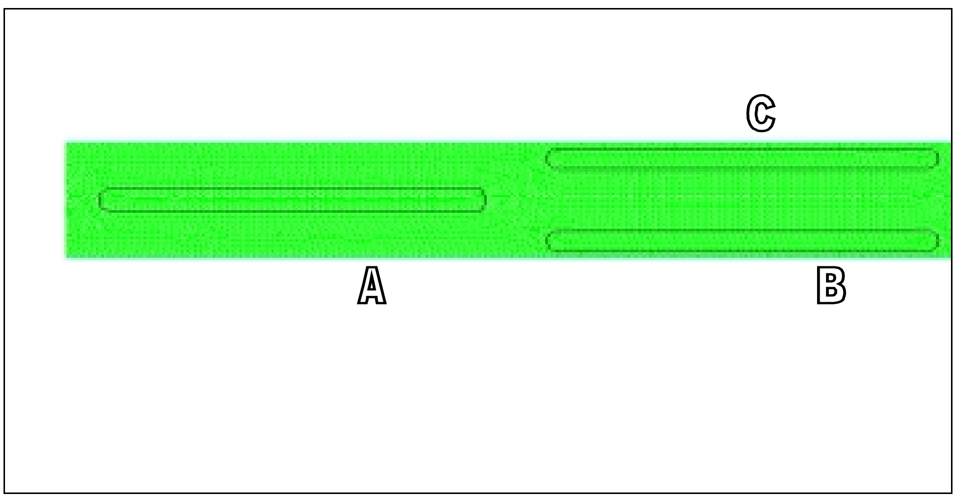

Figure 1: The Computational domain of helium side

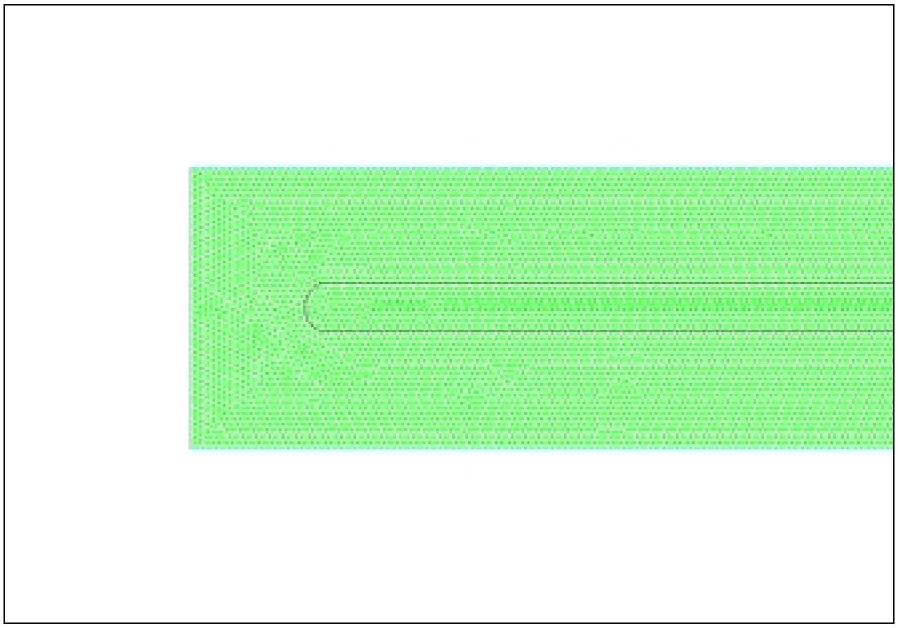

Figure 2: Closer view of the Triangular mesh of the domain near fin A

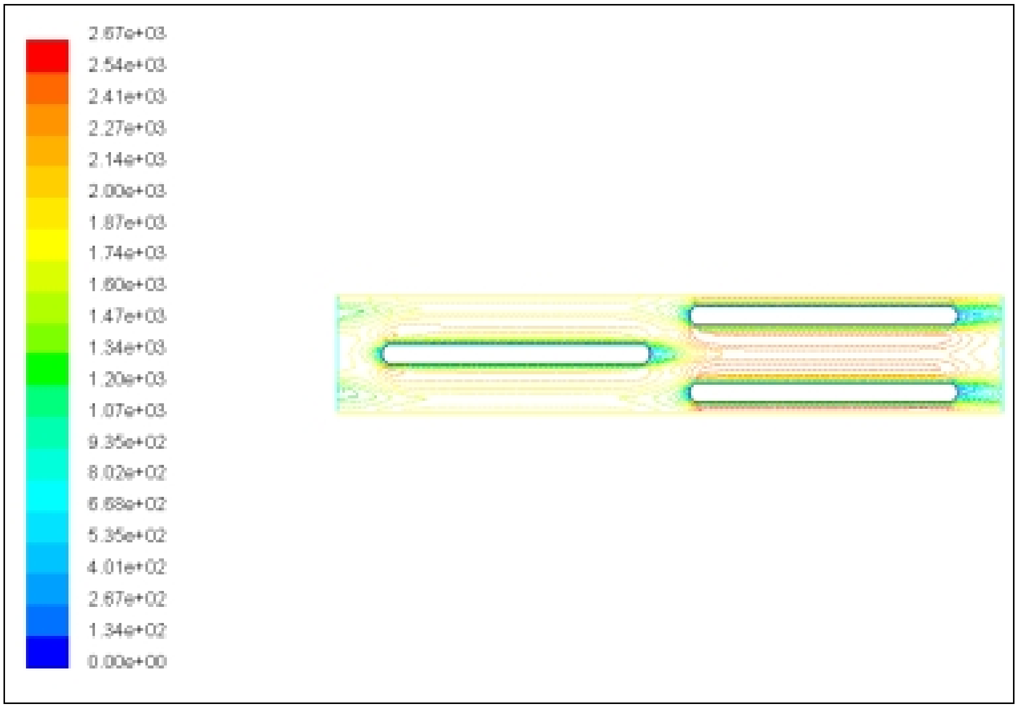

Figure 3: Velocity Contours

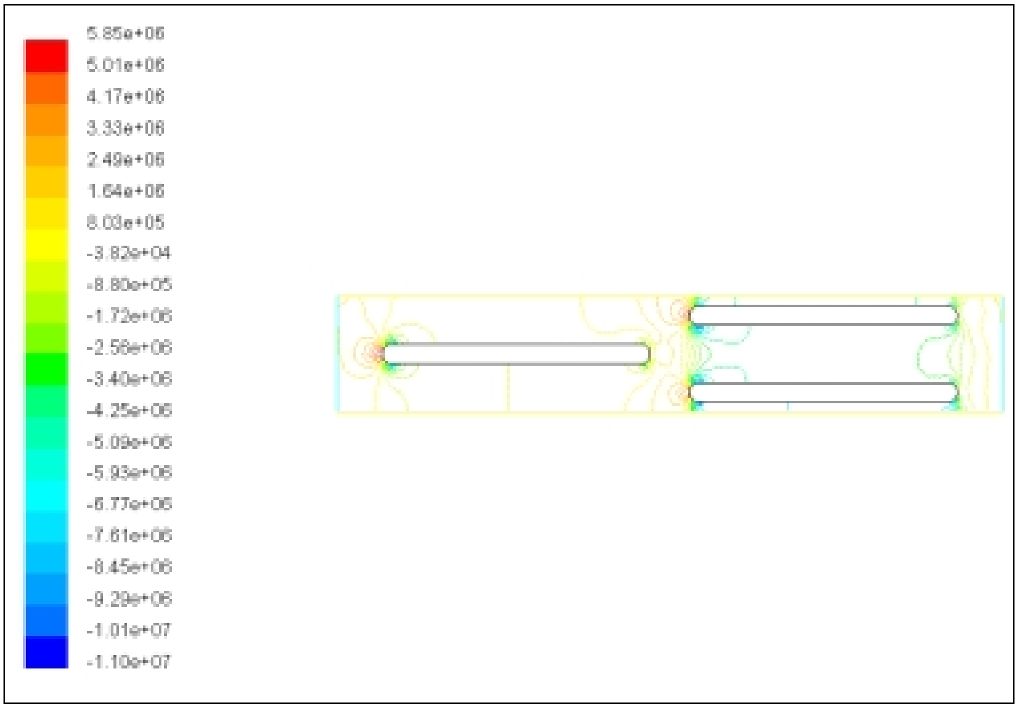

Figure 4: Pressure Contour

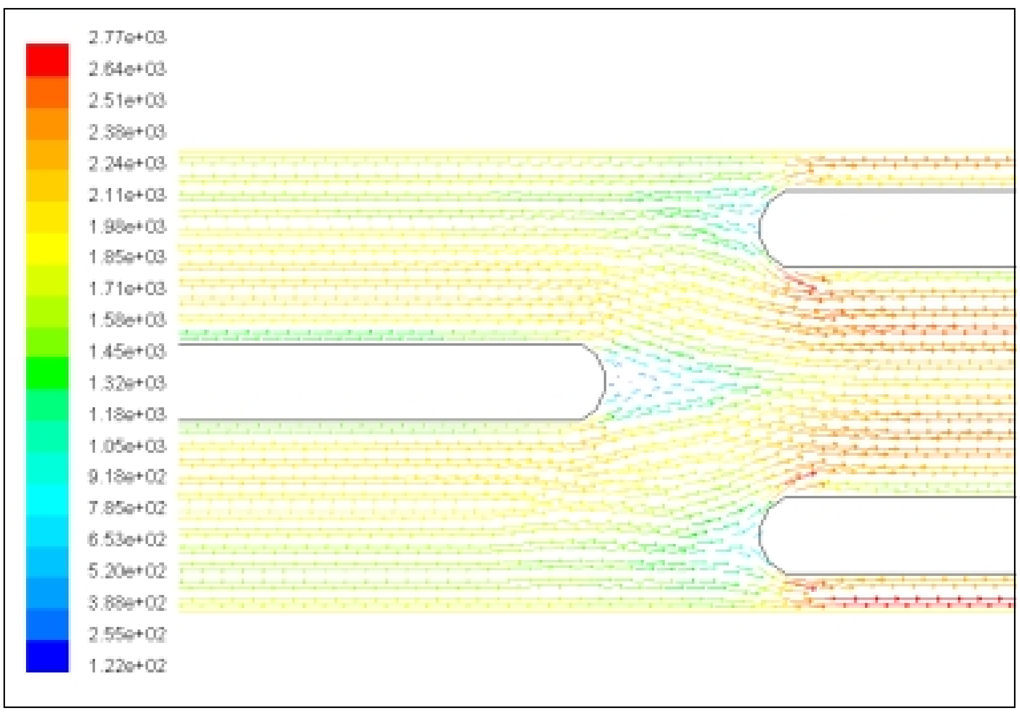

Figure 5a: Velocity vectors leading edge of fins B and C

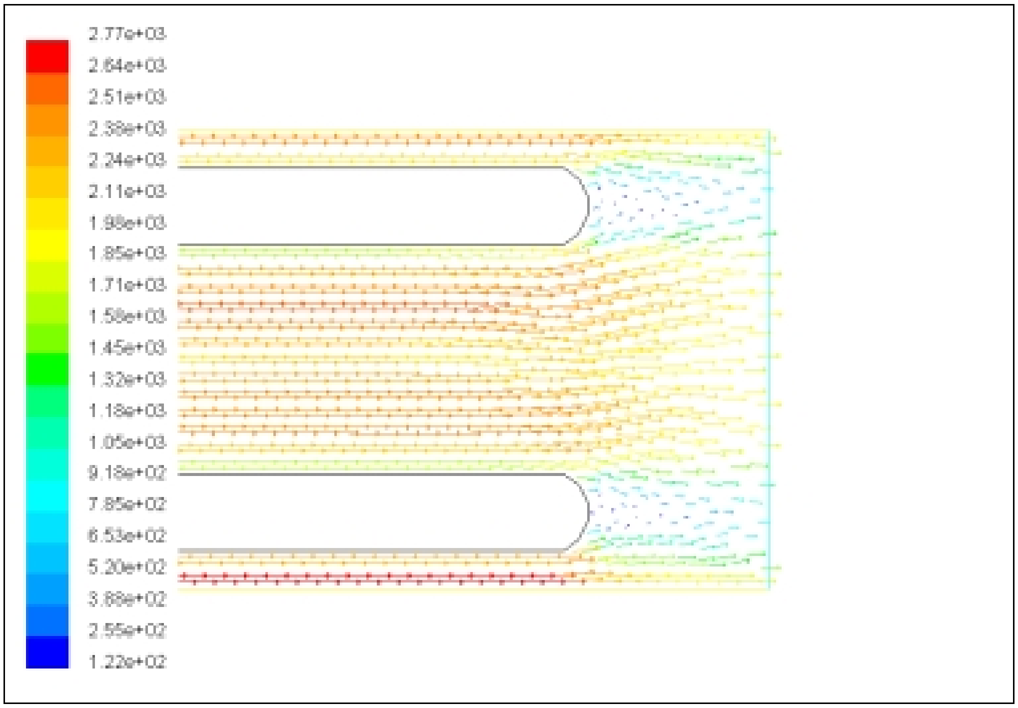

Figure 5b: Velocity Vectors at the trailing edge of Fins B and C

For the same computational domain with the same boundary conditions, iteration is performed with initialized condition set as All Zones and default (No velocity Specified).

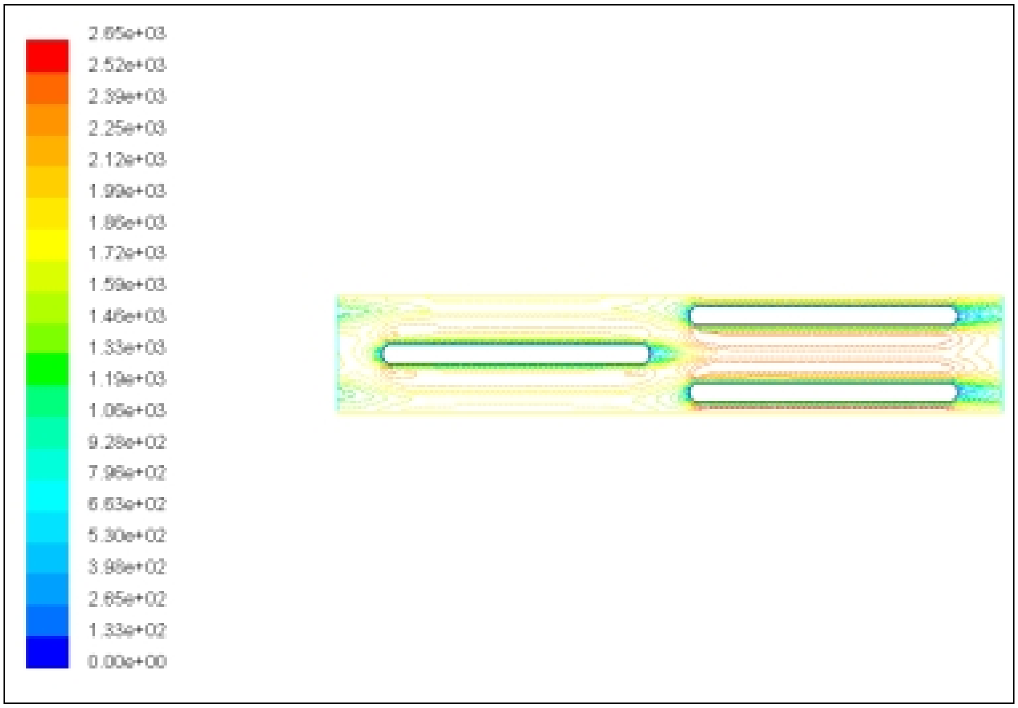

Figure 6: Velocity Contours

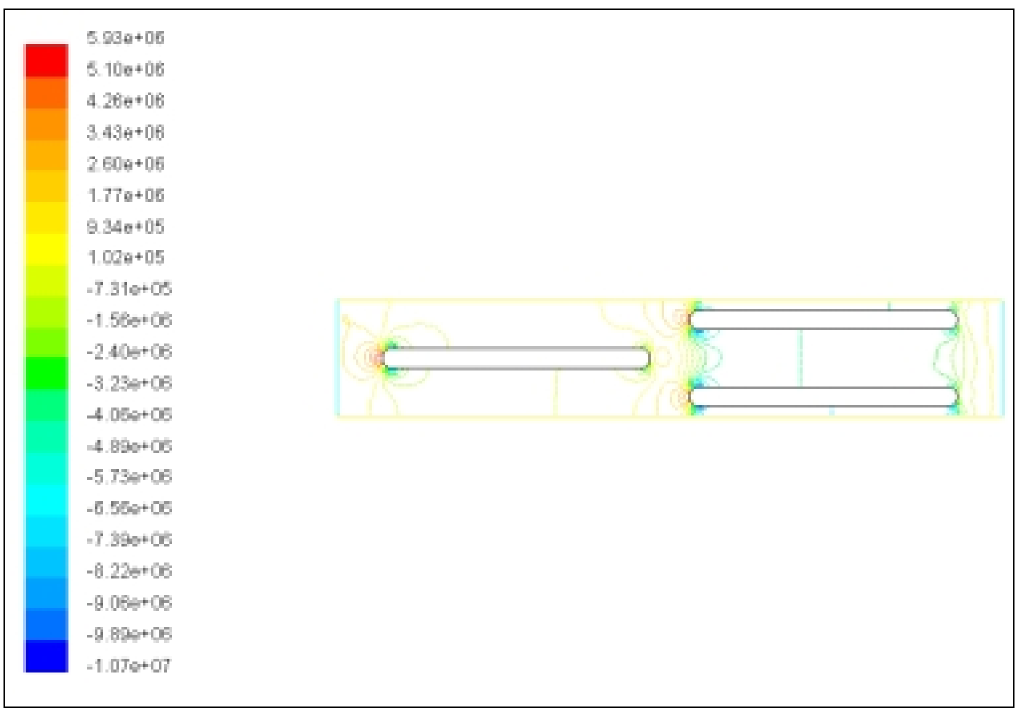

Figure 7: Pressure Contour

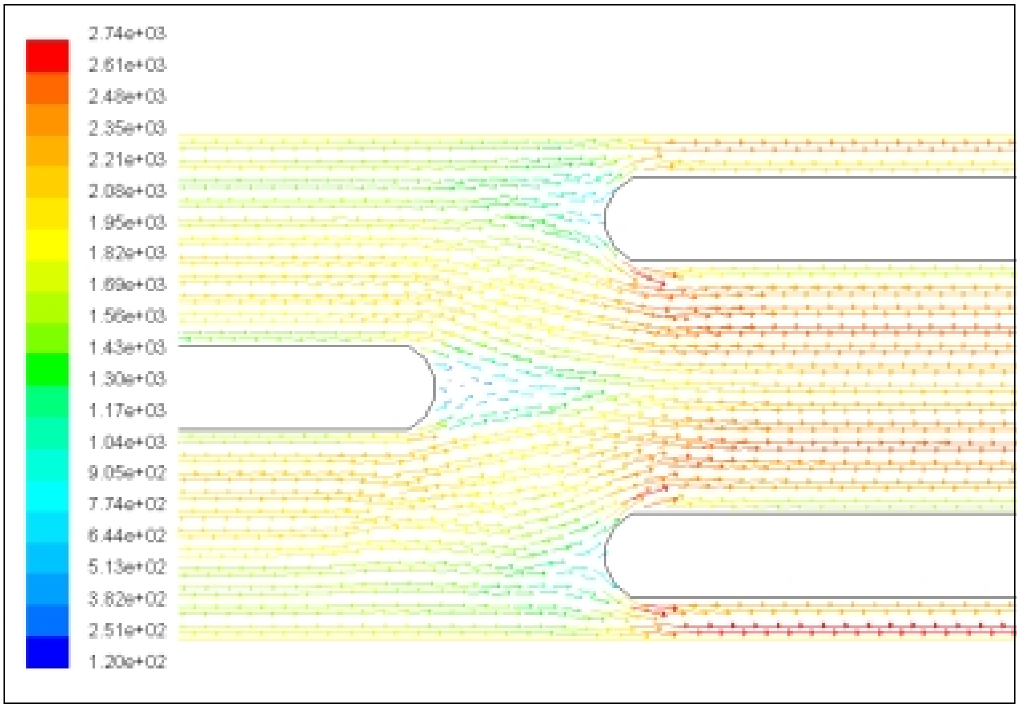

Figure 8a: Velocity vectors at the leading edge of fins B and C

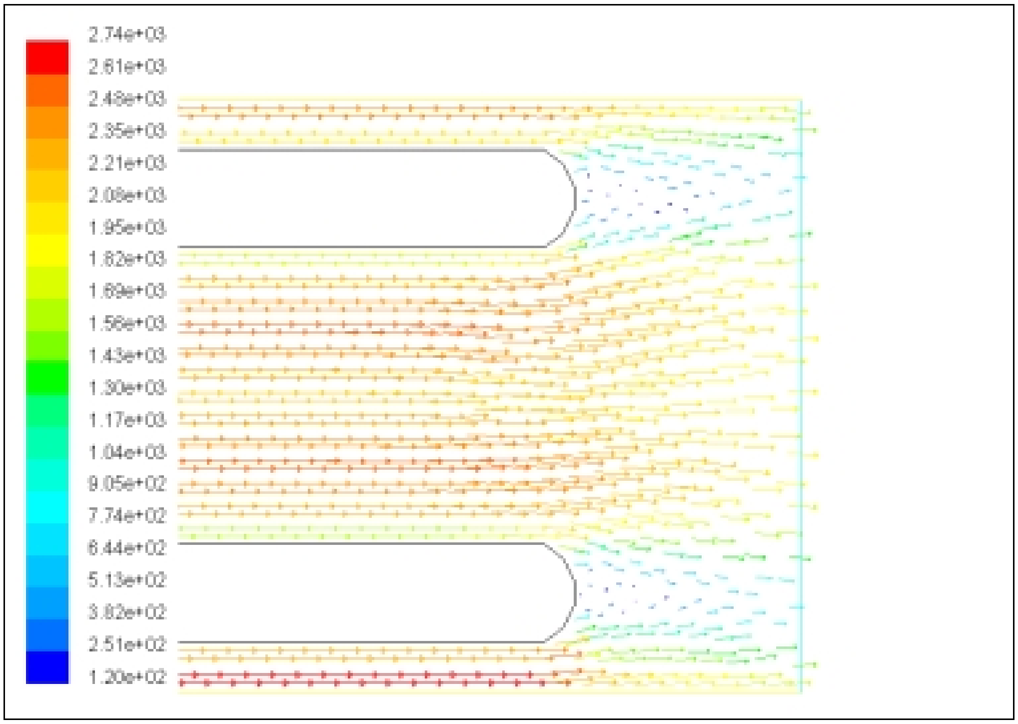

Figure 8b: Velocity vectors at the trailing edge of fins B and C

From the above results it can be implied that the FLUENT output is the same when velocity is specified as 17 m/s or no velocity is specified. The resulting velocity vectors are similar, indicating that FLUENT is able to model fluid flow when the periodic flow condition is specified, input for mass flow rate is given, and the pressure gradient value is calculated by the software itself through iterations.

In the velocity contours and the velocity vectors it is clear that there is flow vortex formed at the edges of fins which according to many references are the regions where the maximum heat transfer takes place.

Materials Characterization and Testing-Highlights

- **Objectives and Scope**
  - Work with DOE NE nuclear hydrogen research and development program elements on materials for hydrogen production.
  - Identify candidate materials and performance requirements for nuclear hydrogen production candidate technologies.
  - Based on DOE R&D priorities, initiate materials characterization testing activities (e.g., fabrication of test samples, physical property characterization tests, materials compatibility tests as function of temperature and environment for candidate HTHX materials, and forming, bonding and shaping tests for HTHX design studies).
- **Performance requirements and candidate materials**
  - Based on a preliminary literature review and prior related industrial experience, heat-treated round bars of three different nickel-base alloys, namely Alloy C-276, Alloy C-22 and Waspaloy, have been procured for tensile and polarization testing. The tensile testing will assess stress corrosion cracking (SCC) and elevated temperature mechanical properties. Polarization testing will evaluate the susceptibility of all three candidate alloys to localized corrosion (pitting and crevice) in the aqueous environment of interest (sulfur-iodine) at different temperatures.
  - A fourth Ni-base alloy known as Aerex 350, having high-temperature deformation resistance up to 1350^{o}F, will also be included in the testing program.
- **Testing Matrices**
  - Tensile and polarization testing regimes have not yet been specified.
  - Corrosion testing in HI environments at GA will consider a minimum of four candidate materials for the system $HI/I_2/H_2O$. The materials will be tested at process temperatures and pressure with sample inspection and analysis at 2, 10, and 100 hours exposure. Corrosion testing in HI environments at GA has been enabled by the hiring of a new employee with materials expertise.

- **Sample fabrication and preparation**

    - Machining of tensile specimens of three nickel (Ni)-base alloys, namely Alloy C-22, Alloy C-276 and Waspaloy, is in progress at UNLV. Electrochemical polarization specimens are also being fabricated. Testing will be initiated as soon as the specimens are available.

- **Test and analysis implementation**

    - UCB and UNLV will collaborate in permeability testing of composite coupons to gases like helium and liquid metals. Leak testing under stress will also be examined.

    - UCB's permeation testing will be augmented by post-testing Scanning Electron Microscopy and Transmission Electron Microscopy of samples at UNLV.

    - Flow loop testing of coupons might also be prosecuted at UNLV.

    - UCB has designed a helium permeation test device for testing melt-infiltrated composite samples. In the current design, a disk of material is clamped between o-rings and stressed by applying helium pressure to one side, the He leakage rate is measured.

    - UCB is fabricating the test fixture and will verify its performance. In terms of deflection and stress levels, room-temperature aluminum is a good plate material to simulate the LSI carbon-carbon composites. Therefore, aluminum plates will be used to test the fixture**.**

    - To obtain stresses up to 100 MPa in the sample with reasonable forces against the o-rings, calculations indicate that test sample disks around 50 mm in diameter and 1.0 to 1.5 mm thick should be the best to test.

<u>Scaled Demonstration Testing-Highlights</u>

- **Objectives and Scope**

    - Work with DOE NE R&D program to identify highest priority candidates for HTHX designs for Gen IV hydrogen production.

    - Design and fabricate scaled HTHX section designs.

    - Conduct heat transfer and performance testing of HTHX components for lab-scale and pilot plant conditions.

    - Interface with Very High Temperature Reactor demonstration project.

- **Collaboration Meetings**
    - The initial quarter of the UNLVRF HTHX Project included several meetings among collaborators to define the focus of the research program, down select potential research areas, and select initial research projects.

- **Composite Materials Coupon Testing Program Proposal**
    - A preliminary research plan has been proposed to start some initial testing experiments with composite material coupons.

Scaled Demonstration Testing-Technical Summary

- It is proposed that composite material coupons should be obtained to test impermeability to gases such as helium, liquid metal infiltration, and leak testing under mechanical stress. GE Power Systems Composites and a German aerospace company manufacture standard components, and may be able to make coupons to specifications. However, a smaller company may better suit our small needs. Briefly, the test program will consist of the following phases:
    - **Leak Test** - using the UCB apparatus to test 2" D disks, 1-1.5 mm thick. One side will contain pressurized He. Tensile stresses up to 100 MPa will be applied to the point of potential cracking;
    - **Characterization -** using UNLV facilities for post-testing examination such as SEM and TEM;
    - **Loop Test** - installing coupons in a flow loop potentially sited at UNLV; and
    - **HTHX Component Tests -** repeating tests with heat exchanger elements in place of coupons.

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