Manuscript ID: DOEBTO-UMD-8221-18-JT1

Full Citation: Tancabel, J., Aute, V., and Radermacher, R. **"Review of Shape and Topology Optimization for Design of Air-to-Refrigerant Heat Exchangers."** *17th International Refrigeration & Air Conditioning Conference*, West Lafayette, Indiana, USA. Paper ID: 2437. July 9-12, 2018.

Review of Shape and Topology Optimization for Design of Air-to-Refrigerant Heat Exchangers

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ABSTRACT

Air-to-refrigerant heat exchangers (HXs) have been the topic of exhaustive research as they are fundamental components of HVAC&R systems. It has been well-established that the large airside thermal resistance dominates the HX thermal resistance, and thus significant research efforts have focused on improving the air-side performance of these heat exchangers. As HXs continue to become more compact, thermal resistance reduction is typically realized through the utilization of extended secondary heat transfer surfaces such as fins. However, past research has shown that the thermal-hydraulic trade-offs provided by fins are often not attractive enough to warrant their use, especially for small diameter tubes. Yet, the inadequate primary surface area provided by compact HXs essentially mandate the necessity of fins to meet thermal resistance requirements. In recent years, advancements in computational tools such as Computational Fluid Dynamics (CFD) and optimization algorithms, coupled with the advent of additive manufacturing technologies, have allowed engineers to expand conventional HX design ideologies to include such concepts as shape and topology optimization. This lends itself directly to primary heat transfer surface optimization and even the potential removal of finned surfaces altogether. This paper presents a comprehensive literature review investigating air-to-refrigerant HX shape and topology optimization. The fundamentals of both shape and topology optimization, model development, and experimental validations are all separately discussed. Studies featuring manufactured prototypes and/or experimentally validated optimal designs are treated with additional emphasis. This paper concludes by identifying key research gaps and proposing future research directions for HX shape and topology optimization.

Keywords: heat exchanger, heat transfer enhancement, shape optimization, topology optimization

1. INTRODUCTION

As worldwide population continues to grow, researchers have dedicated significant time and effort in developing efficient and environmentally-friendly solutions to combat ever-increasing energy resource demands. In particular, the development of smaller, lighter, and more efficient air-to-refrigerant heat exchangers (HXs) has come to the forefront, as these components are critical to systems such as air-conditioners (condensers/evaporators) and automobiles (radiators), to name a few.

As HXs become more compact, the required thermal resistance can only be achieved through the utilization of extended secondary surfaces, e.g., fins. This is especially so for small characteristic diameter tubes, whose inadequate primary surface area alone cannot achieve the required thermal resistance. However, recent work (Bacellar *et al.*, 2017a) has suggested the existence of a trade-off between finless and finned surfaces. As tube diameter decreases, finless surfaces realize higher heat transfer coefficients at lower hydraulic resistances compared to finned surfaces. Significant research on the use of small diameter, round, finless tubes in HX design and their potential performance improvements have been well-studied (Paitoonsurikarn *et al.*, 2000; Saji *et al.*, 2001; Kasagi *et al.*, 2003; Bacellar *et al.*, 2014; Chen *et al.*, 2016). Advancements in computational tools such as Computational Fluid Dynamics (CFD) and optimization algorithms, coupled with the advent of additive manufacturing (AM) technologies, have allowed engineers to expand upon conventional HX design ideologies to include such concepts as shape and topology optimization, two methodologies which directly lend themselves to primary heat transfer surface optimization and, potentially, the complete removal of finned surfaces altogether.

This paper serves to be a comprehensive literature review investigating air-to-refrigerant HX shape and topology optimization, specifically tube shape and topology optimization. First, fundamentals and formal definitions of shape and topology optimization are discussed for self-consistency. The next sections investigate the models and methodology of HX shape and topology optimization studies in literature. Particular emphasis is placed on studies featuring manufactured prototypes and/or experimentally-validated optimal designs. We conclude with a discussion of the research trends and gaps.

2. FUNDAMENTALS OF SHAPE AND TOPOLOGY OPTIMIZATION

2.1 Shape Optimization

Shape optimization refers to finding a shape which maximizes / minimizes a given cost function according to a prescribed problem and its design constraints. A common shape optimization problem from literature is design for reduced drag, e.g., automobile body detailing (Hucho *et al.*, 1976) and airfoil shape (Hicks and Henne, 1978; Lutz and Wagner, 1998). In the context of this work, HX shape optimization refers to finding optimal HX tube shapes.

Typically, shape optimization problems are treated as standard optimization problems utilizing parameterized geometry (Ding, 1986; Haftka and Grandhi, 1986; Samareh, 1999, 2001). In the past, shape optimization candidate geometries were severely limited by conventional manufacturing methods, especially at the microscale. Yet, advancements in AM have allowed tube wall thicknesses on the order of 150 microns (Arie *et al.*, 2017a,b). This grants flexibility to pursue increasingly complex tube shapes at significantly smaller sizes.

2.2 Topology Optimization

Topology optimization is typically defined as "the material distribution method for finding the optimum lay-out" of a structure that maximizes / minimizes a given cost function according to a prescribed problem and its design constraints (Bendsøe and Sigmund, 2013). This methodology has been applied to truss design and MEMS manufacturing through etching and deposition (Bendsøe and Sigmund, 2013). Similar to shape optimization, topology-optimized designs have been restricted by conventional manufacturing constraints. Recently, AM has provided an avenue to pursue complex topologies which could not be manufactured using conventional methods (Brackett *et al.*, 2011; Zegard and Paulino, 2015). In the context of this manuscript, HX topology optimization refers to finding the optimal distribution of tubes in space, i.e., finding the optimal longitudinal / transverse pitch ratios.

2.3 Combined Shape & Topology Optimization

First, note that round tube diameter falls outside the definitions of both shape and topology optimization. Therefore, studies utilizing tube diameter must also include tube spacing design variable(s) to be considered here. Further, note that the definitions of HX shape and HX topology optimization are by design fully disjoint, i.e., one can occur without the other. Alternatively, these concepts can be combined into a coupled framework to investigate the benefits of simultaneous shape and topology optimization. Figure 1 presents a concept heat exchanger which (i) could be realized through shape and topology optimization and (ii) demonstrates the incredible design flexibility granted to engineers by AM (3T RPD®, 2015). Figure 2 presents an arbitrary coupled shape-topology optimization. Here, a baseline elliptic tube is shape-optimized to a more streamline, airfoil-like shape while the longitudinal and transverse pitches are also optimized (Hilbert *et al.*, 2006; Bacellar *et al.*, 2016a,b, 2017a,b).

Figure 1: Metal additively manufactured concept heat exchanger (3T RPD® Ltd., 2015)

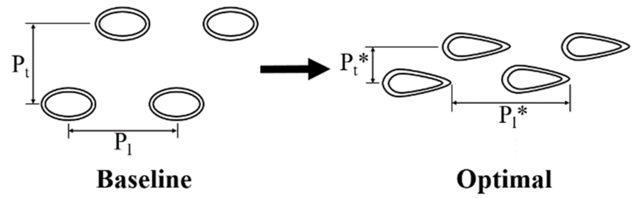

Figure 2: Coupled shape-topology optimization based on Hilbert et al. (2006) & Bacellar et al. (2016a,b; 2017a,b).

3. LITERATURE SURVEY AND MAJOR FINDINGS

3.1 Model Development

Many models have been developed for HX optimization. This section discusses common models found in literature and those models' assumptions, strengths, and limitations. The authors note that in-depth model discussions are beyond the scope of this literature review; readers are referred to the original references for such details.

3.1.1 Analytical models: Analytical models are built from first-principles of solving the coupled mass, momentum, and energy conservation equations after applying applicable assumptions. Analytical models commonly assume fully-developed, steady, incompressible flow with constant fluid properties, yielding the mass, momentum, and energy conservation equations presented in Equations (1), (2), and (3), respectfully. These equations are typically further simplified through non-dimensionalization based on the problem of interest.

$$\nabla \cdot \vec{u} = 0 \tag{1}$$

$$\rho\left(\vec{u} \cdot \nabla\right)\vec{u} = -\nabla P + \mu \nabla^2 \vec{u} \tag{2}$$

$$\vec{u} \cdot \nabla T = \alpha \nabla^2 T \tag{3}$$

Analytical models are limited in that well-defined tube shape are required; for example, round tubes are often assumed (Stanescu *et al.*, 1996). Also, two-dimensional flow is often assumed since tube length is significantly larger than HX depth. This also eliminates consideration of end effects. Another common assumption is laminar flow since laminar thermal and velocity boundary layer theory is well-developed. Still further assumptions must be made to yield a solvable system. These may include simple boundary conditions such as isothermal tubes and constant properties since simple expressions for fluid properties are not available beyond the ideal gas law.

3.1.2 Numerical models: Numerical models solve the conservation equations using a numerical discretization on an appropriate computational domain and are commonly referred to as CFD models or simulations (Pantakar, 1980). CFD software, commercial or self-developed, convert the conservation equations into numerically-solvable algebraic equations using any of the following methods: (i) finite difference method (FDM), (ii) finite element method (FEM), or (iii) finite volume method (FVM). Figure 3 presents a sample computational domain which may be used for a CFD simulation of a staggered, round tube HX segment.

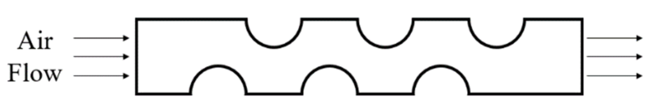

Figure 3: Sample round tube HX segment computational domain.

CFD can model any geometry that can be parameterized into a computer. This allows for shape and/or topology optimization on-the-fly, as opposed to analytical models. Moreover, CFD simulations can study laminar or turbulent flow so long as proper turbulence models are identified. As an increased advantage over analytical models, CFD models allow researchers to utilize variable fluid properties, resulting in more accurate results. Some common assumptions in CFD models include: fully-developed, steady, incompressible flow, and isothermal tube walls. However, CFD possesses some inherent disadvantages. The selection of incorrect flow regime model may lead to incorrect results. Further, CFD models must be exhaustively verified and validated to ensure their accuracy, typically through experimentation. This could require time-consuming and costly prototyping, especially for shape-optimized designs which may require unconventional manufacturing methods.

3.1.3 Brief Note on Experimentation: Current HX literature is saturated with experimental studies for almost all HX varieties. However, physical prototypes which cannot be easily shape- and/or topology-optimized on-the-fly. Therefore, studies which experimentally characterize HX thermal-hydraulic performance fall beyond the scope of this literature review. Only literature pertaining to HX shape and topology optimization validation is discussed.

3.2 Literature Survey

A summary of HX shape and topology optimization models in literature is presented in Table 1. The major findings of these studies are presented in Table 2. Detailed discussions on research trends, optimization approaches, experimental validations, and research gaps appear in the following sections.

Table 1: Summary of HX Shape and Topology Optimization Models

Reference	Model(s)*	Study	Working Fluid(s)	Geometry Info.	Algorithm(s)	Validation
Stanescu *et al.* (1996)	Analytical; Numerical (FEM)	Topology	Airside only	Round tube; no fin; staggered	Parametric study	Yes
Wright (2000)	Numerical (Eqns)	Topology	Air/R410A	Round tube; plain fin	Exhaustive search	No
Matos *et al.* (2001)	Numerical (FEM)	Shape & Topology	Airside only	Round, elliptic tube; no fin; staggered	Parametric study	Yes
Aspelund (2001); Stewart & Shelton (2010)	Numerical (Eqns)	Topology	Air/R410A	Round tube; plain fin; staggered	Simplex method	No
Matos *et al.* (2004)	Numerical (FEM)	Shape & Topology	Airside only	Round & elliptic tube; plain fin; staggered	Parametric study	Yes
Hilbert *et al.* (2006)	Numerical (CFD)	Shape	Airside only	NURBS tube; no fin; staggered	MOGA with CFD simulations	No
Abdelaziz (2009) Abdelaziz *et al.* (2010)	Numerical (CFD)	Topology	Air/Water	Webbed fin round tube; inline; staggered	MOGA with metamodels	Yes
Saleh *et al.* (2010); Aute *et al.* (2013)	Numerical (CFD)	Topology	Air/Water	Webbed fin round tube; inline; staggered	MOGA with metamodels	No
Hajadollahi *et al.* (2011)	Numerical (Eqns)	Topology	Air/Water	Round tube; plain fin; staggered	NSGA-II	No
Qian *et al.* (2013)	Numerical (Eqns)	Topology	Air/R32; Air/R134a	Round tube; plain fin; microchannel	MOGA	No
Bacellar *et al.* (2014)	Numerical (CFD)	Topology	Air/Water; Air/R410A	Round tube; no fin; inline; staggered	MOGA with metamodels	No
Daroczy *et al.* (2014)	Numerical (CFD)	Topology	Airside only	Round tube in hexagonal channel	NSGA-II	No
Ranut *et al.* (2014)	Numerical (CFD)	Shape	Airside only	NURBS tube; no fin; staggered	NSGA-II; FMOGA-II	No
Bacellar *et al.* (2015)	Numerical (CFD)	Shape & Topology	Air/Water	Four tube geometries	MOGA with metamodels	No
El Gharbi *et al.* (2015)	Numerical (CFD)	Shape	Airside only	Round, elliptic, droplet tube; no fin; staggered	Parametric study	No
Huang *et al.* (2015)	Numerical (Eqns)	Shape & Topology	Air/R134a, Air/R290;	Variable tube and fin shapes	MOGA	No
Bacellar *et al.* (2016a)	Numerical (CFD)	Shape & Topology	Air/Water	Three tube geometries	MOGA with metamodels	Yes

Bacellar *et al.* (2016b)	Numerical (CFD)	Shape & Topology	Air/Water	Round tube, webbed NURBS tube; staggered	MOGA with metamodels	No
Felber *et al.* (2016)	Numerical (Eqns)	Topology	Air/Water	Microchannel; microstructure pin fin	Parametric study	Yes
Huang *et al.* (2016)	Numerical (Eqns)	Topology	Air/R410A	Round tube; no fin; staggered	MOGA	No
Arie *et al.* (2017a,b)	Numerical (Eqns)	Shape & Topology	Air/Water	Manifold microchannel	MOGA with metamodels	Yes
Bacellar *et al.* (2017a,b)	Numerical (CFD)	Shape & Topology	Air/Water	NURBS tube; no fin; staggered	MOGA with metamodels	Yes
Damavadi *et al.* (2017)	Numerical (CFD)	Shape & Topology	Airside only	Elliptic tube	NSGA-II, neural network models	No
Haertel & Nellis (2017)	Numerical (CFD)	Topology	Air/Water	Microchannel; microstructure pin fin	Method of Moving Asymptotes	No
Huang (2017)	Numerical (CFD)	Shape & Topology	Air/Water	Bifurcated round tube	MOGA with metamodels	Yes
Raja *et al.* (2017)	Numerical (Eqns)	Topology	Air/Water	Round tube; plain fin	Heat transfer search	No
Zhicheng *et al.* (2017)	Numerical (CFD)	Shape	Air/Water	Welded wavy plates	Grey correlation theory	Yes

*Abbreviations: CFD: Computational Fluid Dynamics | Eqns: Equations | FEM: Finite Element Method

Table 2: Summary of Major Findings in HX Shape and Topology Optimization

Reference	Objective Function(s)	Major Findings
Stanescu *et al.* (1996)	• Max q'''	• Opt. spacing (↓) as velocity (↑) and flow depth (↓) • Experimental validation of analytical & numerical models
Wright (2000); Aspelund (2001)	• Max seasonal COP	• Small diameter tubes give higher system COP
Matos et al. (2001)	• Max q'''	• Model validated with Stanescu *et al.* (1996) experiments • $\Delta P_{a,ellipse} < \Delta P_{a,round}$ $h_{a,ellipse} > h_{a,round}$
Matos et al. (2004)	• Max q'''	• Validaton for both circular and elliptic geometries • $M_{Matl,ellipse} < M_{Matl,round}$
Hilbert *et al.* (2006)	• Max ΔT_a; Min ΔP_a	• First paper on HX tube shape parametrization with NURBS • Varying airfoil-like tube shapes
Abdelaziz (2009) Abdelaziz *et al.* (2010)	• Max Q/A_f, Q/V_{HX}, Q/M_{Matl} • Min ΔP_a	• Novel method (offline AAO) to study heat transfer surfaces • DoE evaluated using Parallel Parameterized CFD (PPCFD) • Significant objective function improvements • Validation with prototyped optimal design (±10% agreement)
Saleh *et al.* (2010)	• Max h_a; Min ΔP_a	• Extends Abdelaziz *et al.* (2010) AAO to Online AAO (OAAO) • OAAO opt. designs better or equal to offline AAO opt. designs
Stewart & Shelton (2010)	• Max seasonal COP or Min entropy generation	• Optimize HX as an isolated component or in system context
Hajadollahi *et al.* (2011)	• Max thermal effect • Min cost	• Effectiveness and cost increase with tube diameter and decrease with increasing tube pitch
Aute *et al.* (2013)	• Min ΔP_a, V_{HX}	• AAO (Abdelaziz *et al.*, 2010) metamodels produced using novel adaptive Design of Experiments (DoE) technique • Airside ΔP: ~87% (↓); V_{HX}: ~44% (↓)
Qian *et al.* (2013)	• Max Q • Min entransy dissipation; entropy generation; cost	• No significant difference between capacity, entransy dissipation and between entransy dissipation and entropy generation
Bacellar *et al.* (2014)	• Min ΔP_a, V_{HX}	• Opt. designs 50% smaller, 2-4 times higher material utilization • ΔP_a: 75% (↓); h_a: 100% (↑)
Daroczy *et al.* (2014)	• Min equivalent ΔP, V_{HX}	• Opt. designs symmetric about channel centerline • Potential to include HX size minimization as objective function
Ranut *et al.* (2014)	• Max Q; Min ΔP_a, ΔP_r	• Second paper on HX tube shape parameterization with NURBS • Low ΔP_a tubes have low h_a and ΔP_r compared to bluff-body tubes

Bacellar *et al.* (2015)	• Min ΔP_a, V_{HX}, A_f	• First paper mentioning webbed shape-optimized tubes • Opt. designs have 50% size, material, and ΔP_a reduction • Approach temperature: 20% (↓)
El Gharbi *et al.* (2015)	• Max Nusselt number, Euler number, entropy generation	• Direct comparison of round, elliptic, and droplet shape tubes • Round tubes: best heat transfer; highest pressure drop • Elliptic / droplet tubes: Similar thermal-hydraulic performance
Huang *et al.* (2015a)	• Min M_{Matl} ; Max Q	• First variable geometry HX study in literature • Material usage: 35% (↓); V_{HX}: 43% (↓)
Bacellar *et al.* (2016a)	• Min ΔP_a, V_{HX}	• Validation with metal AM prototype • Leverage boundary layer detachment/reattachment mechanism • V_{HX} and pumping power: 50% (↓)
Bacellar *et al.* (2016b)	• Min A_f • Max $h_a/\Delta P_a$, j/f, novel PEC	• New PEC to fairly compare multiple HX geometries • HX decision-making criteria (Multi-Attribute Utility Function) • Significant face area reduction and aspect ratio improvement
Felber *et al.* (2016)	• Min V_{HX}	• Partial validation with polymer 3D-printed prototype • Low polymer thermal conductivity limit model applicability
Huang *et al.* (2016)	• Max Q • Min entransy dissipation; entropy generation; cost	• Low capacity: capacity entransy dissipation largely similar • Higher capacity: entransy dissipation and capacity should be considered as separate objective functions
Arie *et al.* (2017a,b)	• Max COP, gravimetric heat transfer density	• Direct laser metal sintering for prototyping and validation • Gravimetric heat transfer density: 60% (↑)
Bacellar *et al.* (2017a,b)	• Min ΔP_a, V_{HX}	• First coupled shape-topology opt. framework in literature • First shape-optimized prototype of NURBS-tube HX • Framework validated for dry condition, tested for wet condition
Damavadi *et al.* (2017)	• Max j; Min f	• Smaller tubes result in better heat transfer and worse ΔP
Haertel & Nellis (2017)	• Max HX conductance	• Airside microstructure optimized to any topology • Prototypes manufacturable using polymer AM • Topology-opt. allows low conductivity material utilization
Huang (2017)	• Min pumping power, V_{HX}	• Novel bifurcated HX tubes • ΔP_a: 35%(↓); A_f: 78%(↓); Ref. charge: >40%(↓) • Model framework validated using polymer AM prototype
Raja *et al.* (2017)	• Min coil weight, total annual cost	• Opt. design weight: 16% (↓) • Opt. design annual cost: 9% (↓)
Zhicheng *et al.* (2017)	• Max Webb efficiency (Webb, 1981)	• Developed optimized, and prototyped concept wavy plate HX • Opt. design efficiency approx. double the baseline

4. DISCUSSION

4.1 Major Research Trends

HX shape and topology optimization encompasses many applications including but not limited to radiators, condensers, and evaporators. However, many studies only consider airside thermal-hydraulic performance. Most studies focus on finned or finless round or elliptic tube HXs with single-phase water as refrigerant. Other studies consider refrigerants such as R32, R134a, R290, and R410A. However, as new low Global Warming Potential (GWP) refrigerants come online, it is unclear whether optimized HXs maintain design performance when using drop-in replacement refrigerants. To this end, future research should consider next generation, low GWP refrigerants. Moreover, a significant number of objective functions have been studied, e.g., HX capacity, airside pressure drop, airside heat transfer coefficient, coil volume, and entransy dissipation, to name a few. In general, objective functions are tailored to improve HX performance while reducing the overall coil footprint. However, it is unclear whether Performance Evaluation Criteria (PEC) such as capacity and/or pressure drop adequately and fairly compares the performance benefits of one tube shape and topology versus another.

Shape and topology optimization studies are almost exclusively computational (see Table 1). Two common methodologies are utilized: (i) equation-based models and (ii) FEM/CFD simulations. Equation-based models are derived from first-principles and coded into numerical solvers such as Engineering Equation Solver® (EES®) or Matlab®. Such models often utilize well-known heat transfer and pressure drop correlations to determine thermal-hydraulic performance. FEM and CFD simulations are typically developed and solved using commercial software packages (ANSYS® Fluent, COMSOL®), and are often more complex and, thus, more accurate.

Most optimization studies only consider topology optimization. This could be for many reasons. Equation-based models utilizing heat transfer and pressure drop correlations rely on a priori knowledge of tube geometry, fixing the tube shape. It may also be of interest to optimize an HX for an available set of tubes. Further, shape and topology optimization may result in HX designs that are manufacturable only with non-conventional methods, e.g., AM (Bacellar *et al.*, 2016a,b, 2017a,b; Felber *et al.*, 2016; Arie *et al.*, 2017a,b; Haertel and Nellis, 2017; Huang, 2017).

Early shape optimizations decreased pressure drop penalty by transforming round tubes to be more elliptical (Matos *et al.*, 2001, 2004). Recent research has shifted focus to optimizing parameterized tube shapes. A select few studies utilize Non-Uniform Rational B-Splines (NURBS) for tube shape parameterization (Hilbert *et al.*, 2006; Ranut *et al.*, 2014; Bacellar *et al.*, 2016a,b, 2017a,b). NURBS present a unique opportunity as they can parameterize almost any smooth curve without significant loss of accuracy (Farin, 1990). That is, NURBS can parameterize circles, airfoil-shapes, and any shape in between, allowing shape optimization on-the-fly.

4.2 Optimization Approach

HX shape and topology optimization methodology is quite diverse (see Table 1). Early studies utilized parametric studies or computationally expensive exhaustive searches. Recent technological advancements have yielded computationally efficient optimization algorithms which, when coupled with equation-based and/or CFD models, can solve complex optimization problems. A majority of studies utilize genetic algorithms (GA's) such as: (i) Multi-Objective Genetic Algorithm (MOGA) (Deb, 2001), (ii) Non-Sorting Genetic Algorithm II (NSGA-II) (Deb *et al*, 2002), and (iii) FMOGA-II (Rigoni, 2010). The reader is referred to applicable literature for discussion on GA fundamentals. In particular, MOGA is used in multiple contexts, so some additional discussion is fitting.

4.2.1 Multi-Objective Genetic Algorithms: MOGA appears in three contexts: (i) MOGA in equation-based models, (ii) MOGA with CFD, and (iii) MOGA in Approximation-Assisted Optimization (AAO). In Contexts (i) and (ii), the MOGA evaluates an initial population, creates a new population based on prescribed evolutionary operations, and reevaluates the new population until termination. Context (ii) runs a new CFD simulation for each individual, which is very computationally expensive considering that a single optimization could consist of thousands of simulations.

4.2.2 AAO with MOGA: To reduce computational costs resulting from running new CFD simulations at each step, AAO methods have been applied to HX optimization (Abdelaziz, 2009; Abdelaziz *et al.*, 2010). In AAO, HX thermal-hydraulic performance is approximated with surrogate metamodels constructed by simulating the design space with a Design of Experiments (DOE). The MOGA evaluates the metamodels rather than running new CFD simulations for each individual. By front-loading all CFD, significant computational resources are saved. As an additional note, FMOGA-II is quite similar to AAO with MOGA (Rigoni, 2010; Ranut *et al.*, 2014).

5. OPTIMAL DESIGN PROTOTYPING AND EXPERIMENTAL VALIDATION

Optimization aims to develop next generation technologies to replace the current state-of-the-art. However, optimized, especially shape-optimized, HXs face significant tech-to-market barriers due to difficulties which may arise from utilizing conventional manufacturing methods. Further, non-round, shape-optimized tubes likely lack the structural integrity round tubes, potentially requiring additional structural analysis, i.e., Finite Element Method (FEM), simulations to verify tube structural integrity. Therefore, it is of interest to prototype optimal designs to (i) validate optimization frameworks and (ii) provide the HVAC industry with evidence to further investigate new HX geometries. Manufactured prototypes and experimentally-validated designs are now discussed in detail.

5.1 Conventional HX Prototyping

Conventional HX prototyping focuses on non-AM prototypes. Stanescu *et al*. (1994) performed experiments on a round tube array to experimentally validate their findings on optimal tube spacing. Matos *et al.* (2001) validated their CFD models using the experiments of Stanescu *et al*. (1994). Matos *et al.* (2004) also prototyped a finned round tube HX and an optimal finned elliptic tube HX to validate their new work. Both studies by Matos *et al*. (2001; 2004) shape- and topology-optimized baseline round tubes to more streamline elliptic tubes. Abdelaziz (2009) experimental validated his unified HX design and optimization framework for a single tube row. Zhicheng *et al.* (2017) experimentally validated a wavy plate HX design using a gas-water heat recovery system.

5.2 Additive Manufacturing

Most shape-optimized HXs cannot be economically manufactured using conventional methods due small feature sizes and thin material thicknesses. However, AM represents a unique opportunity since complex geometries can be easily produced provided that geometry features fall within prescribed limits. HXs have been prototyped using both polymer and metal AM, which are treated separately.

5.2.1 Polymer AM HXs: Multiple HXs have been prototyped using polymer AM, indicating its viability and future potential. Arie *et al.* (2017a,b) utilized 3D laser welding to fabricate a manifold microchannel HX in polymer, while Felber *et al.* (2017) utilized polymer AM to prototype and validate a microchannel HX featuring topology-optimized airside microstructures. Huang (2017) applied polymer AM to validate a novel bifurcated round tube HX concept.

5.2.2 Metal AM HXs: Bacellar *et al.* (2016a; 2017a,b) experimentally validated their multi-scale analysis and shape optimization framework using a metal AM prototype. Their novel, shape-optimized, metal AM HX remains the first of its kind. As a result, metal AM HX prototyping could represent a significant research opportunity in HX design.

6. CONCLUSIONS

Air-to-refrigerant HXs are critical components of HVAC systems which possess considerable airside thermal resistance. Reducing said resistance through optimization presents a significant research and market opportunity. More recently, advancements in computational tools, optimization algorithms, and AM have allowed engineers to integrate primary heat transfer surface (shape) and topology optimization concepts into the HX design process. The current study reviews air-to-refrigerant HX shape and topology optimization in detail with particular emphasis on manufactured prototypes and/or experimentally-validated optimal designs. Shape- and/or topology-optimized designs have shown potential to outperform state-of-the-art HXs for multiple objectives such as increased capacity for reduced pressure drop, HX volume, or HX weight. Numerous researchers have prototyped optimal designs using both conventional techniques and metal and polymer AM, proving the viability of shape and topology optimization in HX design. Research gaps include, but are not limited to, the following:

- Most studies, especially shape optimization studies, only consider single-phase (radiator) applications. Future research should focus on two-phase (condenser, evaporator) shape- and topology-optimized HXs.
- Two-phase HX optimization studies often consider only one refrigerant. As new refrigerants come online, it is unclear whether optimized HXs would maintain their design performance when operating using drop-in replacements. More robust HX designs could be achieved by optimizing for multiple refrigerants.
- There is a general lack of HX optimization studies which consider next generation, e.g., low GWP, refrigerants. Some examples of fluids to consider include: CO_2, ammonia, R290, and R1234yf, upon others.
- Open literature lacks a single set of PEC to fairly compare HX performance regardless of tube shape. Such PEC could accelerate the tech-to-market potential of shape- and topology-optimized HXs with the goal of replacing conventional tube-and-fin and microchannel HXs in the HVAC industry.
- To the best of the authors' knowledge, no studies in literature consider tube structural integrity. Therefore, optimal design mechanical feasibility is questionable until structural analysis is conducted after the fact. A framework including structural analysis could allow optimization algorithms to simultaneously achieve structurally sound and thermal-hydraulically optimal designs, reducing the number of required simulations.

NOMENCLATURE

A_f	Face area	(m²)	T	Temperature	(K)
COP	Coefficient of Performance	(–)	u	Fluid velocity	(m/s)
f	Friction factor	(–)	q'''	Volumetric heat transfer	(W/m³)
h_a	Airside heat transfer coefficient	(W/m²K)	V_{HX}	HX coil volume	(m³)
j	Colburn factor	(–)	ΔP_a	Airside pressure drop	(Pa)
M_{Matl}	Material mass	(kg)	ΔP_r	Refrigerant pressure drop	(Pa)
P	Pressure	(Pa)	ΔT_a	Airside temperature change	(K)

P_l	Longitudinal pitch	(m)	*Greek Letters*		
P_l^*	Optimal longitudinal pitch	(m)			
P_t	Transverse pitch	(m)	α	Thermal diffusivity	(m²/s)
P_t^*	Optimal transverse pitch	(m)	μ	Dynamic viscosity	(Pa-s)
Q	Heat transfer rate	(W)	ρ	Fluid density	(kg/m³)

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ACKNOWLEDGEMENT

This work was supported by the United States Department of Energy Grant Number DE-EE0008221 and the Modeling and Optimization Consortium at the University of Maryland.