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Thermo-hydraulic performance reliability, sensitivity and cross-model transferability of perforated helical twisted-tape inserts

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ABSTRACT

This study proposes a computational framework to address the uncertainties and evaluates the reliability of the computational predictions of the thermal-hydraulic design, between different models, for perforated helical twisted-tape (*P*-HTT) inserts. The contribution is methodological – it is not a new insert geometry, CFD dataset or conventional deterministic optimization, but rather, an experimentally validated empirical model is treated as an engineering prediction model and model behavior on the domain boundaries, uncertainty-conditioned model performance, convergence of the model numerical solution, and model transferability are tested. The audited *P*-HTT model is evaluated over $Re = 6000$ – 20000 , $d/w = 0.2$ – 0.6 , and $s/w = 1$ – 2 . The outcome of the boundary analysis indicates that the nominal maximum is found at $\eta \approx 1.283$, $Re = 6000$, $d/w = 0.20$ and $s/w = 2.0$ which is a domain constrained optimum. A discrete search and a continuous search are compared and it is found that there is no contradiction with the optimum value of interpolation. Moreover, the numerical stability of the Monte Carlo method, with a Monte Carlo sample size ranging from 103 to 2.5×10^5 , is demonstrated, with the value of the reference uncertainty $\eta_{5\%}$ remaining at around 1.248 over the clearly defined reference uncertainty scenario. Logarithmic-elasticity analysis showed that the models have approximately $3.84\times$ and $7.38\times$ different effect size when using an independent correlation with the perforated twisted-tape under Reynolds number and perforation diameter respectively conditions, while the direction of the effect of both these variables can be transferred from one model to the other. Additionally, the analysis can be separated into the trends which are common to both tested models and the sensitivities which are related to the model structure to allow a meaningful interpretation of the optimal values of the thermo-hydraulic performance under conditions of uncertainty.

Keywords: Perforated helical twisted tape, Thermo-hydraulic performance, Uncertainty quantification, Reliability analysis, Monte Carlo simulation, Sensitivity analysis, Cross-model transferability, Thermal transport augmentation

1. Introduction

The use of passive heat-transfer enhancement devices to augment convective transport by enhancing swirl, secondary flow and disruption of the boundary layer is common. The study of twisted-tape and similar swirl-flow devices has been carried out in great detail due to their geometric simplicity and their ability to enhance the heat transfer by a significant amount, but with increased friction and pumping demands (Eiamsa-ard *et al.*, 2006; Seemawute *et al.*, 2010; Singh *et al.*, 2016; Omid *et al.*, 2017) [1, 2, 3, 4]. To overcome the nature of these trade-offs, a number of perforation, cutting, counter-swirl and hybrid inserts have been developed (Nanan *et al.*, 2014; Güneş *et al.*, 2015; Maithani *et al.*, 2020; Bhuiya *et al.*, 2013; Bhuiya *et al.*, 2016; Suri *et al.*, 2017; Suri *et al.*, 2018; Vaisi *et al.*, 2020; Nakhchi *et al.*, 2021; Dirker *et al.*, 2021; Xiong *et al.*, 2021) [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16].

(Nanan *et al.*) [5] experimentally studied the thermo-hydraulic performance of helical twisted tapes with perforations and derived empirical correlations for the Nusselt number, friction factor and thermal performance factor. Loose-fit perforated tapes (Güneş *et al.*, 2015) [6], porosity effects (Bhuiya *et al.*, 2013; Bhuiya *et al.*, 2016) [8, 9], multiple square perforations (Suri *et al.*, 2017; Suri *et al.*, 2018) [10, 11], discontinuous perforated turbulators (Vaisi *et al.*, 2020) [12] and other geometries of perforations (Nakhchi *et al.*, 2021) [13, 14] have been studied. These studies confirm that perfusion and optimization of geometry are well known and not new ideas. More recently, passive inserts have been investigated along with machine learning and response surface optimization, energy/exergy assessment and entropy-generation analysis (Singh *et al.*, 2025; Göksu *et al.*, 2025; Kumar *et al.*, 2026) [17, 18, 19]. Thus, generic claims of newness are no longer defensible, merely based on perforation or optimization, RSM, or machine learning.

Another issue is how to interpret deterministic optima derived from empirical correlations. The approach of designing a heat-exchanger under uncertainty has an extensive methodological history: Monte Carlo analysis

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has been applied to propagate heat design uncertainty (Badar *et al.*, 1993) [20], a deterministic optimum does not necessarily yield the most reliable design, as shown by reliability-based sensitivity analysis (Azarkish *et al.*, 2019) [21] on heat-transfer problems, interval robust optimization has been applied to heat exchanger design (Tian *et al.*, 2021) [22], and recently, uncertain operating conditions have been integrated into the plate-fin heat-exchanger design (Gao *et al.*, 2023) [23], and reliability-based design optimization has been extended to shell-and-tube heat exchangers (Jafari-Asl *et al.*, 2024) [24]. But, such reliability-oriented concepts are not often applied in questioning the published optimum of an empirical performance correlation for a perforated helical twisted-tape.

Portability is the second un-resolved issue. Insert studies that are related to this report the same qualitative descriptors (Reynolds number, perforation ratio, pitch, twist ratio, and performance factor), and the dimensionless variables and architectures are different from one related insert study to another. This can create unhelpful levels of precision when you use direct aggregation. Today's study only tests for transferability in the case of physically analogous factors, and does so using the logarithmic elasticities, thus allowing a comparison of sensitivity direction but not assuming that different geometries have a common coefficient.

Therefore it is not a review and the work is formulated as original correlation-based computational work. The goals are: (i) to see if the primary P -HTT optimum is an interior optimum or a consequence at a boundary of the design space; (ii) to compare discrete design space consistency versus continuity; (iii) to measure uncertainty conditioned results for reliability and Monte Carlo convergence; (iv) to test the conclusions against explicit scenario uncertainty; and (v) to identify the sensitivity directions that transfer to an independent perforated twisted-tape model and the quantitative effects that are architecture specific.

2. Hypotheses

Seven testable hypotheses were developed to evaluate the reliability of the predictions of thermo-hydraulic performance, their sensitivity, and the ability to transfer between the models. They discuss the influence of important operating and geometric parameters, the robustness of the domain-constrained optimum in the presence of uncertainty, and the numerical stability of the Monte Carlo (MC) reliability analysis.

H1: The main P -HTT correlation shows that a decrease in the thermal performance factor (η) occurs with an increase in Reynolds number (Re).

H2: A higher perforation-diameter ratio brings down the value of η for both the perforated twisted-tape models that were audited.

H3: The sensitivity magnitudes can be carried between related insert architectures.

H4: The existence of a universal optimum can be concluded if the correlations of related perforated twisted-tape are pooled.

H5: The optimal value is consistently greater than the lower limit of model uncertainty, $\eta = 1$, with published model error and the assumed moderate model error scenario.

H6: The apparent optimum is not an interior stationary optimum, but rather is due to the validity-domain bounds.

H7: Estimates of reliability are numerically robust to the number of Monte Carlo trials.

Nomenclature

The following abbreviations are used: d/w - perforation-diameter ratio, f - friction factor, N - Nusselt number, P/D - Helical pitch-to-diameter ratio, Pr - Prandtl number, Re - Reynolds number, s/w - perforation-spacing ratio, S_x - logarithmic elasticity with respect to x , y/w - twist ratio, η - thermal performance factor, $\eta_{5\%}$ - fifth percentile of η .

3. Mathematical model and computational method

3.1 Audited primary correlations

The basic model is the experimental correlation developed by (Nanan *et al.*) [5]. It is used only within its published validity domain: $Re = 6000-20000$, $d/w = 0.2-0.6$, $s/w = 1-2$, with $P/D = 2$ & $y/w = 3$. Approximate errors in the prediction of N , f and η are reported to be $\pm 4\%$, $\pm 6\%$ and $\pm 3\%$ respectively (Nanan *et al.*, 2014) [5].

(1)

$$Nu = 0.035Re^{0.795}Pr^{0.4}(d/w)^{-0.067}(s/w)^{0.086}$$

(2)

$$f = 1.915Re^{-0.299}(d/w)^{-0.067}(s/w)^{0.094}$$

(3)

$$\eta = 4.058Re^{-0.145}(d/w)^{-0.045}(s/w)^{0.055}$$

3.2 Domain mapping, flexibility and boundary testing

To evaluate the dense deterministic grid, the whole empirical domain was considered. The thermal-performance correlation is a power law, therefore the logarithmic elasticities are the corresponding exponents: the logarithmic elasticity of the relation between thermal performance and residential building area is $S_{Re} = -0.145$, the logarithmic elasticity of the relation between thermal performance and the cost/unit area is $S_{d/w} = -0.045$, and the logarithmic elasticity of the relation between thermal performance and the number of units is $S_{s/w} = +0.054$. These values directly reflect the percentage response of η to a 1 per cent change in the input, and establish whether or not a stationary optimum inside the interior is mathematically feasible.

3.3 Discrete-versus-continuous consistency

To avoid the appearance of new experimental evidence, the dense-grid result was verified with the documented levels of geometric factors $d/w = \{0.2, 0.4, 0.6\}$ and $s/w = \{1, 1.5, 2\}$. The check was not an actual experimental test of the present authors, but rather an interpolation-consistency test.

3.4 Provenance of uncertainty and Monte Carlo procedure

The sources of uncertainty were categorized based on their source. The $\pm 3\%$ prediction error is source supported (Nanan *et al.*, 2014) [5]. Only scenario variables were the Reynolds-number and the geometric uncertainty, for which 95% half-widths of 5% and 2.5% respectively were introduced as baseline. They are not claimed to be measured manufacturing tolerances. Gaussian perturbations were sampled and then cut off to conform to the range published. The reliability has been assessed by $P(\eta > 1)$ and the 5th percentile $\eta_{5\%}$. To check the convergence, the Monte Carlo number was raised from 10^3 to 2.5×10^5 . This method is based on the same general concepts of Monte Carlo uncertainty propagation and reliability analysis methods developed in the field of designing heat-exchangers (Badar *et al.*, 1993; Azarkish *et al.*, 2019) [20, 21].

3.5 Stress test

For the scenarios of Re and the geometry, the uncertainty ranges were multiplied by 0.5, 0.75, 1.0, 1.25, and 1.5, but the published model-error envelope of η was left unchanged. The aim was to determine if the qualitative conclusion is sensitive to any particular one scenario.

3.6 Cross-model transferability

The independent model of Güneş and Karakaya [6] was employed just to ensure the model transferability as it has different variables and domain. It has the following thermal-performance relation: $S_{Re} = -0.0378$ and $S_{d/D} = -0.0061$. No averaging or pooling was performed for the Nanan and Güneş relations. Qualitative direction was considered to be transferable if the signs agreed, and architecture dependent if they disagreed, in terms of magnitude.

4. Results and discussion

4.1 Domain-constrained optimum and boundary effect

The maximum for the below primary domain is reached at $Re = 6000$, $d/w = 0.20$, $s/w = 2.0$, with $\eta \approx 1.283$. This reproduces the maximum performance given by (Nanan *et al.*) [5] which gives a self-check of

the performance. But the optimum is not an interior one. The power law structure drives the optimum towards the lower Re boundary, towards the lower d/w boundary, and towards the upper s/w boundary, therefore monotonically towards the optimum. It is therefore not global optimum as it is restricted by the domains, but domain-constrained optimum.

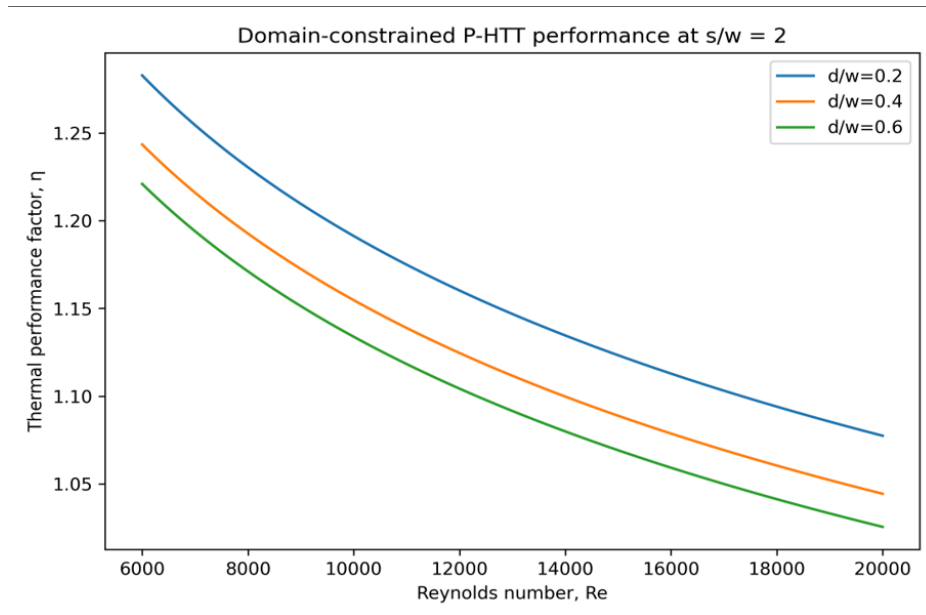


Figure 1. Primary P-HTT thermal performance response to Reynolds number at $s/w = 2$.

This is the most crucial interpretation of boundaries, since the optimization algorithms can make a mathematically simple monotonic endpoint look like an advanced discovery within the algorithm. The

present analysis makes an explicit distinction between the design recommendation in the empirical domain and statements about behaviors in other domains.

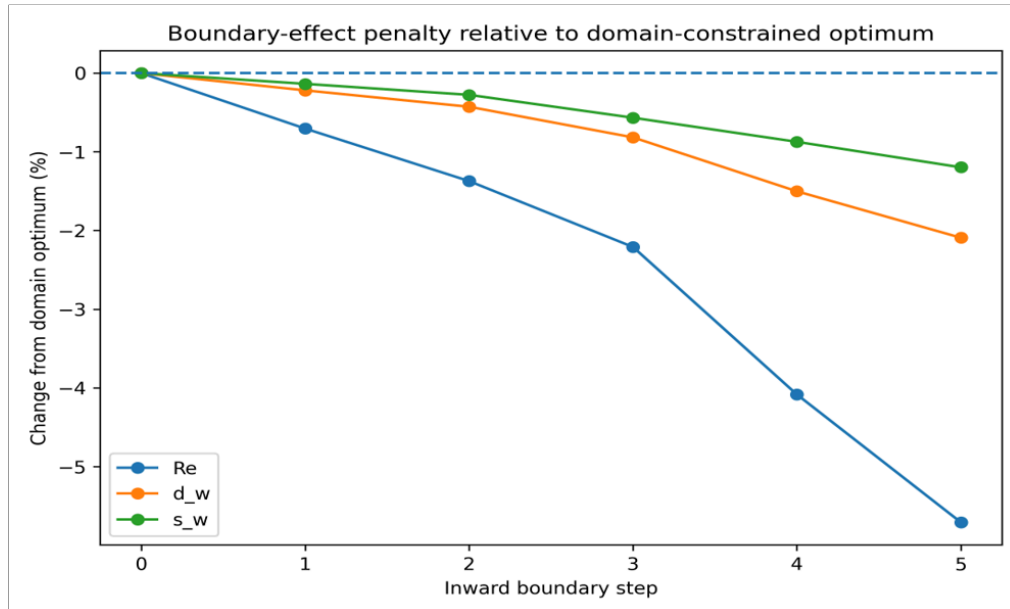


Figure 2. Performance penalty produced by moving inward from the domain-constrained optimum.

4.2 Discrete-versus-continuous verification

The optimum direction, and the boundary geometry are the same for the dense continuous grid and discrete documented geometry levels. So, the optimum obtained by interpolation is not a contradictory opti-

mum. This isn't new experimental proof, but it does alleviate one methodological worry: The principal optimum conclusion isn't a result of choosing untested intermediate geometric ratios.

4.3 Monte Carlo convergence and reliability

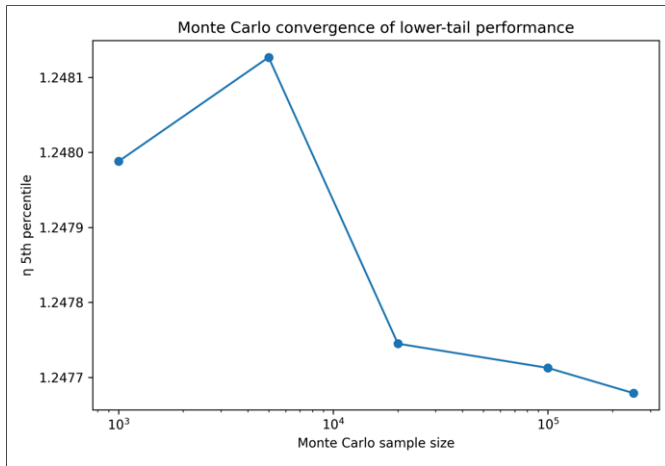


Figure 3. Monte Carlo convergence of the fifth-percentile thermal performance factor.

As more samples are taken the Monte Carlo results approach the target. For $N = 250,000$, the value of $\eta_{5\%}$ is about 1.248, and the numerical precision for the baseline scenario is reported to be 1.00, resulting in an estimated value of $P(\eta > 1) = 1.00$. Its importance is that under these assumptions the lower tail performance has a significant margin of safety over $\eta = 1$.

4.4 Stress-test robustness

The qualitative conclusion that $\eta_{5\%}$ is greater than unity at the primary domain-constrained optimum is unaffected by the range of variation of the assumed operating/geometric by $\pm 50\%$ around the baseline. This increases the robustness of the conclusion, which is not synonymous with the experimentally measured tolerance robustness.

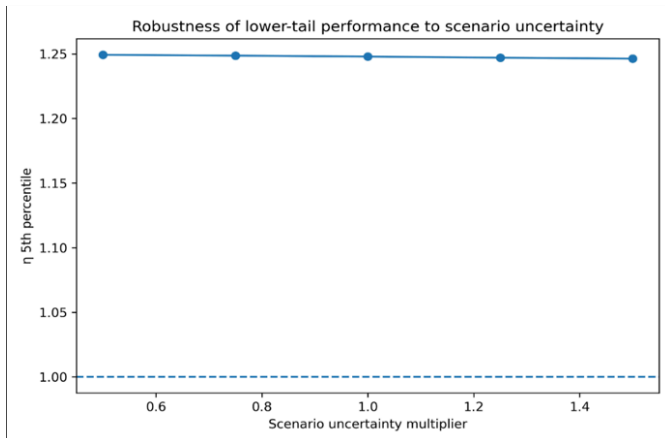


Figure 4. Lower-tail performance under scaled operating/geometric uncertainty scenarios.

4.5 Cross-model transferability

The (Nanan) [5] and Güneş-Karakaya [6] correlations independently predict negative Reynolds-number elasticities and negative perforation-diameter elasticities. Therefore, H1 and H2 are supported at the level of sensitivity direction. However, the magnitudes differ substantially: $|S_{Re}|$ is about 3.84 times larger in the P-HTT model, and the perforation-diameter elasticity magnitude is about 7.38 times larger. H3 is therefore rejected. This distinction is practically important: a designer may trust the direction of change more readily than the numerical rate of change when transferring conclusions between architectures.

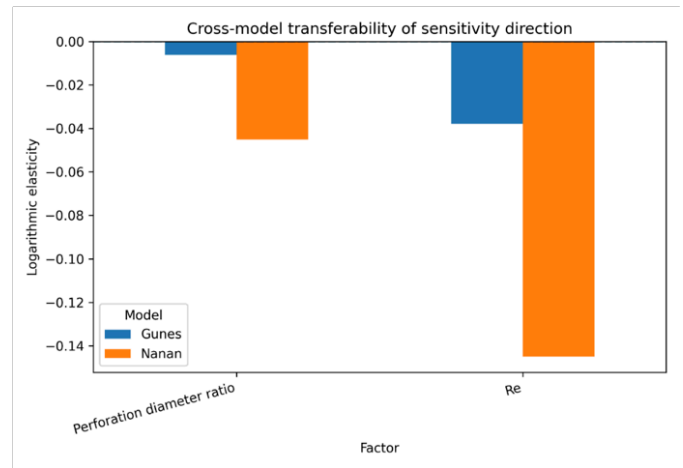


Figure 5. Cross-model logarithmic elasticities for physically analogous factors.

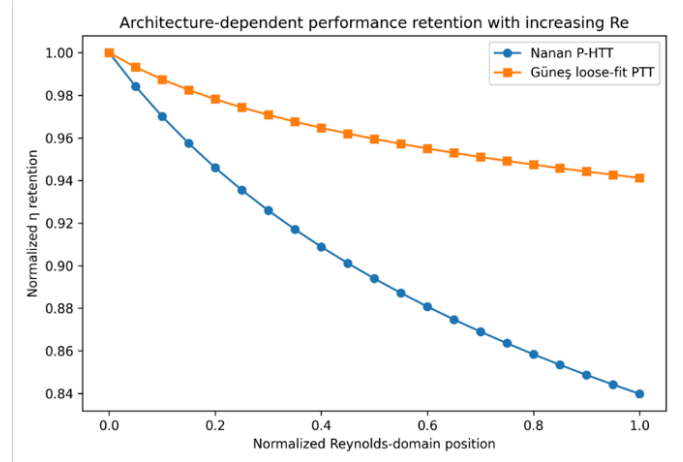


Figure 6. Normalized performance retention across the Reynolds-number domains of the two audited models.

4.6 Relationship to recent optimization literature

Modern works, in turn, justify claims for modernity which are restricted in scope. Helical inserts have been reported to be optimized by machine learning (Singh *et al.*, 2025) [17] and PV/T systems have been optimized with perforated twisted tapes using the RSM algorithm (Göksu *et al.*, 2025) [18]; entropy-based optimization has been used for perforated double-tapes (Kumar *et al.*, 2026) [19]. These developments are not an attempt to use optimization or machine learning or perforation, but rather just a confirmation that this is not what the contribution of the present work is. The innovation is that the contribution is based on an interrogation of a validated empirical optimum from a reliability perspective, on the explicit diagnosis of the boundaries, on the convergence/stress testing, and on the test for transferability without pooling of incompatible geometries.

4.7 Hypothesis outcomes

5. Engineering implications

The practical advice is not generic but may be specific to a particular situation. In the primary P-HTT model, the parameters with maximum negative effect, namely, small Re , small d/w and large s/w , maximize the thermal performance factor within the published domain. However, only the signs of the Re and perforation-diameter effects are transferable across models, with the magnitudes being still architecture dependent. Thus, to use an empirical insert correlation in a specific design, it is necessary to use it as an architecture-specific design tool, and the deterministic optimum should be backed up by a domain statement, uncertainty statement, and a transferability statement before it can be confidently recommended for robust engineering use.

Hypothesis	Outcome	Evidence	Interpretation
H1	Supported	Negative Reynolds-number elasticity in both audited models.	Negative Reynolds-number elasticity in both audited models.
H2	Supported	Negative perforation-diameter elasticity in both audited models.	Negative perforation-diameter elasticity in both audited models.
H3	Not Supported	Sensitivity magnitudes differ by approximately $3.84\times$ and $7.38\times$ for $\backslash(Re\backslash)$ and perforation-diameter ratio, respectively.	Sensitivity magnitudes differ by approximately $3.84\times$ and $7.38\times$ for $\backslash(Re\backslash)$ and perforation-diameter ratio, respectively.
H4	Not Supported	The compared correlations have non-equivalent geometries, variables, and validity domains.	The compared correlations have non-equivalent geometries, variables, and validity domains.
H5	Supported conditionally	$\eta_{5\%} \approx 1.248 > 1$ under the published model error and defined baseline uncertainty scenario.	Reliability is supported only under the specified model and uncertainty assumptions.
H6	Supported	The signs of the power-law exponents force the optimum toward the validity-domain boundaries.	The signs of the power-law exponents force the optimum toward the validity-domain boundaries.
H7	Supported	$\eta_{5\%}$ stabilizes as the Monte Carlo sample size increases to 250,000.	The reported reliability metric demonstrates numerical convergence with respect to sample size.

6. Limitations

This study is based solely on the correlation and does not involve the creation of new experimental measurements or CFD flow fields. The validity and error structure of the main empirical model are passed on to the reliability results. The operating and geometric magnitudes are not measured manufacturing statistics, but are scenario assumptions. Transferability between models is only possible for physically comparable parameters – parameters that are not geometrically comparable are not combined. If the performance is beyond the published domain, it is unknown because the nominal optimum is on the correlation boundary. Lastly, while this set contains recent studies of optimization and reliability, the novelty claim is confined to the specific interrogation of reliability/boundary/transferability that is conducted here. Conclusions are therefore “engineering model” conclusions, in lieu of new physical validation.

7. Conclusions

- The audited P -HTT correlation yields a domain-constrained maximum $\eta \approx 1.283$ at $Re = 6000$, $d/w = 0.20$, and $s/w = 2.0$.
- The optimum is not due to an interior stationary point, but is due to the monotonic correlation structure and domain limits.
- The difference between searches based on discrete levels and searches on dense networks is that the former are consistent, as are the latter, and in both cases the optimal value is not contradictory in the interpolation process.
- The convergence at Monte Carlo is acceptable; in the baseline scenario, the value of $\eta_{5\%}$ is about 1.248 and no realization of $\eta \leq 1$ was encountered at the stated Monte Carlo sample size.
- It is found that the stress test with $\pm 50\%$ around the assumed operating/geometric uncertainty does not change the interpretation of the lower tail.
- The directions of sensitivity and of the perforated-diameter are transferred from one independent model of perforated-tape to another, and their values are quite architecture sensitive.
- The principal contribution of this article is the separation of reliable/transferable qualitative design physics from quantitative predictions specific to architecture.

Data and reproducibility statement

The only empirical correlation and documented transformations used in this study were explicitly stated and the numerical results were calculated as a result of these. The analysis package contains the dense

computational grid and the results of the Monte Carlo convergence analyses, the stress test output, the hypothesis matrix and the transferability analyses, which can be accessed as a supplementary material. In this study, no experimental or CFD data are claimed as new. Clearly, published equations, experimental values, and model uncertainties from the literature are different from numerical results obtained from the computational analyses described herein.

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