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THE APPLICATION OF THE WILSON PLOT METHOD TO CONVECTIVE HEAT TRANSFER – LAST ACHIEVEMENTS

Abstract: The paper discusses and presents the application of the Wilson plot method to the variety of issues related to convective heat transfer. The Wilson plot is a remarkable calculation procedure, which enables the analysis and estimation of convection heat transfer coefficient on the basis of experimental measurements of heat exchanger thermal and flow parameters and the evaluation of corresponding correlation equations. The main facility of the Wilson method is that the heat transfer coefficient can be obtained without the requirement of determining the surface temperature. Much attention was paid to clarify the concept of the standard, original Wilson method as well as its modified versions. The issue was presented in the form of the latest literature review, which featured the investigation of convection coefficients obtained by the Wilson method in the following cases: the flow of nanofluids, refrigerants and other working media in conventional and mini/micro channels and micro-tubes as well as heat transfer under boiling/condensation conditions. The validity of the method utilization has been presented and its future prospects have been specified.

Keywords: Wilson plot, convective heat transfer, thermal characteristics, heat exchanger

Nomenclature

A – heat transfer area
A_c – heat transfer area of the cold side
A_h – heat transfer area of the hot side
c_c – specific heat capacity of cold fluid
c_h – specific heat capacity of hot fluid
d_c – diameter on the inner side of the tube

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d_h – diameter on the outer side of the tube
h_c – heat transfer coefficient of the cold side
h_h – heat transfer coefficient of the hot side
L – tube length
m – mass
R_c – thermal resistance of the cold fluid
R_h – thermal resistance of the hot fluid
R_{ovr} – overall thermal resistance
R_w – thermal resistance of the wall
U – overall heat transfer coefficient
v_r – reduced velocity
ΔT_c – temperature difference of the cold side
ΔT_h – temperature difference of the hot side
ΔT_{log} – logarithmic mean temperature difference
$\dot{Q}$ – heat transfer rate
λ_w – thermal conductivity of the wall

1. Introduction

Heat transfer occurs by convection, conduction and radiation. As far as convective heat transfer is concerned, the amount of energy transferred between the solid body and surrounded fluid for a certain temperature difference, is described by the Newton's Law of cooling. It states that heat transfer rate is obtained by the temperature difference between the surface and the fluid, surface area and heat transfer coefficient.

Experimental measurements of heat exchangers require the determination of mean heat transfer coefficients on both sides of heat transfer surface area. The description of convection heat transfer is very complex and the analytical solution requires solving of mass, momentum and energy conservation equations for a specified geometry and fluid properties (Fernández-Seara, Uhía, & Sieres, 2007). Due to complexity of this approach, it is restricted to simple geometrical configurations of heat exchangers and flow passages. In the majority of real-life cases, heat exchangers are of advanced geometry and therefore analytical approach in determination of local heat transfer coefficient is no longer applicable.

According to the Newton's Law of cooling, the experimental determination of heat transfer coefficient (HTC) can be accomplished by measuring temperatures of the surface and the fluid for prescribed geometry, flow and heat conditions (Fernández-Seara, Uhía, Sieres, et al., 2007). However, direct determination of HTC is not always a straightforward task. The experimental approach can be troublesome and not always feasible due to practical obstacles concerning precise measurement of the surface temperature, e.g. the measurement limitations of the temperature sensors or the impossibility of accurate measurement of this temperature. It is also possible that inserting the temperature sensor may disturb the flow field and thereby the temperature distribution. The problem is even more complex with reference to mini- and micro-heat exchangers, where thermal measurements are frequently tough due to small flow passages.

Therefore, an alternative methodologies have been sought, where the experimental determination of surface temperature was not required. These difficulties can be avoided by applying the Wilson plot method, which is characterized by simplicity and widespread application in experimental investigations of heat exchangers.

Wilson method is a technique used for obtaining heat transfer coefficient of individual working fluid, which is based on the determination of overall heat transfer coefficient for variable flow velocity. The Wilson method allows the estimation of convective heat transfer coefficients in a variety of heat transfer problems. It is based on accurate thermal balance of investigated heat exchanger, which requires the evaluation of the overall thermal resistance (Mikielewicz, 2001). From the practical side, it relies on experimental determination of heat exchanger inlet and outlet thermal and flow parameters, while heat transfer coefficient is obtained from corresponding correlation equation and linear regression analysis. Due to the variety of investigated heat transfer cases and extensive development of heat exchangers with progressively more sophisticated geometry, the method has undergone series of modifications in recent years and currently it represents a universal measuring technique applied to broadly defined convective heat transfer.

This paper focuses on the description of research facilities of the Wilson plot method and its application in convective heat transfer research field. The issue was presented on the basis of current open literature and the main focus was put on the determination of thermal characteristics in minichannel heat exchangers and microtubes, also with two-phase heat transfer and during flow of nanofluids and refrigerants. The general concept of the original Wilson method and its validity have been presented and its future prospects have been specified.

2. The description of the standard Wilson method

The development threshold of the Wilson method is dated back to 1915 (Wilson, 1915). It was first applied to the shell and tube heat exchanger in the case of water flow inside a smooth circular tube and vapour condensation on the outer side in order to obtain convective heat transfer coefficients. The main concept of the Wilson method is to separate the overall thermal resistance into individual ones derived from hot and cold fluid convection and conduction through separating wall (Styrylska & Lechowska, 2003), what enables the evaluation of individual heat transfer coefficients. Overall thermal resistance is obtained from experimental measurements, particularly inlet and outlet flow rates and temperatures, on the basis of which the thermal balance of investigated heat exchanger is performed.

In the first approach, Wilson has made several assumptions regarding his method (Sieres, 2020):

- thermal resistances of the wall R_w and of one fluid are constant,
- the heat transfer correlation equation for other fluid is known,
- variations of fluid properties are neglected,
- fouling effects resistance are neglected.

In order to employ the original Wilson method in practise, it is crucial to schedule a series of measurements in a way to keep the flow rate of cold fluid at a constant level and the flow rate on the shell side can be varied arbitrary. Afterwards the order is reversed, which means that the flow rate of the other fluid is established, while the flow rate of the previously constant fluid is changed. It is assumed that during the variation of flowrate, the variation of overall thermal resistance is influenced by the variation of heat transfer coefficient. The thorough description of the concept of the original Wilson method is presented below.

Thermal energy balance of the heat exchanger can be expressed as:

$$\dot{Q} = m_c \cdot c_c \cdot \Delta T_c = m_h \cdot c_h \cdot \Delta T_h \tag{1}$$

At the same time, heat transfer rate can be written with the use of overall heat transfer coefficient *U*, heat transfer area *A* and logarithmic mean temperature difference ΔT_{log}:

$$\dot{Q} = U \cdot A \cdot \Delta T_{log} \tag{2}$$

The product of overall heat transfer coefficient and heat transfer area gives the inverse of overall thermal resistance, which is described by the formula:

$$\frac{1}{R_{ovr}} = U \cdot A \tag{3}$$

Thus, the combination of Eq. (2) and Eq. (3) provides the expression of the overall thermal resistance:

$$R_{ovr} = \frac{\Delta T_{log}}{\dot{Q}} \tag{4}$$

According to Fernández-Seara, Uhía, Sieres et al. (2007) and Sieres (2020), the overall thermal resistance R_{ovr} can be also expressed as a sum of three thermal resistances, which correspond to the cold and hot fluid flow R_c and R_h respectively, and wall thermal resistance R_w, as shown below:

$$R_{ovr} = R_c + R_w + R_h \tag{5}$$

The Eq. (5) can be expanded to the following, more detailed form:

$$R_{ovr} = \frac{1}{h_c \cdot A_c} + \frac{ln\left(\frac{d_h}{d_c}\right)}{2\pi \cdot \lambda_w \cdot L} + \frac{1}{h_h \cdot A_h} \tag{6}$$

It is relevant that Eq. (6) is applicable for cylindrical cross section geometries. If the outer flow is maintained constant, then the corresponding thermal resistances of the hot fluid and the wall, can be also considered constant, which can be written as:

$$R_w + R_h = C_1 \tag{7}$$

Moreover, when assuming constant fluid properties (Fernández-Seara et al., 2005), heat transfer coefficient of the cold fluid during fully developed turbulent flow is proportional to the power function of reduced velocity:

$$h_c = v_r^n \cdot C_2 \tag{8}$$

Therefore, thermal resistance of the cold fluid is proportional to the inverse of the power function of reduced velocity. Hence, the combination of equations (6), (7) and (8), yields to the overall thermal resistance expressed in a form:

$$R_{ovr} = \frac{1}{C_2 \cdot A_c} \cdot \frac{1}{v_r^n} + C_1 \tag{9}$$

Equation (9) has a form of a linear function $y = ax + b$, with a slope equal to $\frac{1}{C_2 \cdot A_c}$ and absolute term b equal to constant C_1 , which is an interception of the line with y-axis. The graphic presentation of the original Wilson plot technique was shown in Fig. 1.

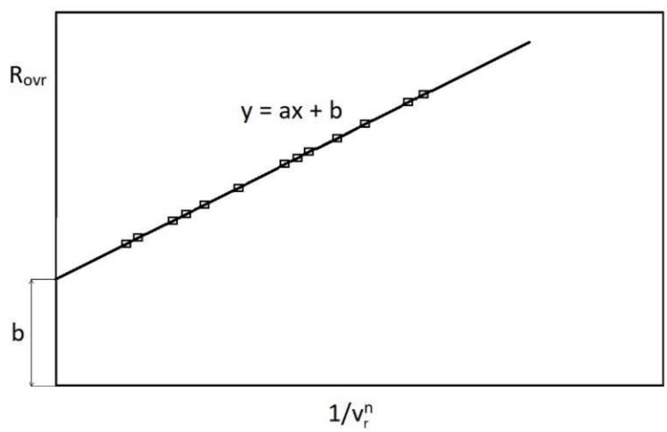

Fig. 1. Graphic interpretation of the standard Wilson plot method

The value of the exponent n in Eq. (9) is selected in such a way that experimentally obtained overall thermal resistance can be represented as a linear function of the expression $\frac{1}{v_r^n}$. The value of n is usually 0.8, however it may be sometimes corrected in order to best fit the experimental results. The straight line equation, which matches the experimental data, is determined analytically by applying linear regression analysis methods. Therefore, constants C_1 and C_2 can be estimated and the inside and outside convection coefficients can be assessed as a function of the cooling liquid velocity (Fernández-Seara, Uhía, Sieres et al., 2007; Fernández-Seara et al., 2005). With the first development of the Wilson method, some general correlations describing the convective heat transfer have appeared in the open literature, which are still in use so far.

Wilson plot method is applicable when thermal resistances on both sides of heat exchanger are of the same order as well as when both fluid flows are uniform. In the original method it is essential to maintain the flow of one fluid constant while altering the flow rate of other fluid, which is often uncomfortable. Moreover, the method is appropriate when the flow on the inner side of the heat exchanger is turbulent and fully developed.

Primary modifications of the Wilson method were characterized by the fact that the mass flow of the fluid was varied as a function of the Reynolds and Prandtl numbers. Nusselt number correlation used to obtain convective coefficients combined the Reynolds and Prandtl numbers, which has a form of Eq. (10):

$$Nu = C \cdot Re^n \cdot Pr^m \tag{10}$$

For simplicity, the values of exponents n and m have to be established first.

Further modifications of the Wilson method resulted from certain limitations imposed by the original version of the method, which is based on number of assumptions, including the consistency of the outside convection coefficient and neglecting the fouling effects as well as prescribed values of n and m exponents of Reynolds and Prandtl numbers in Nusselt number correlation. In the case when either of the condition cannot be accomplished, e.g. the occurrence of surface roughness, which depends on tube design and condition, the parameters initially assumed constant, will vary. Therefore, more advanced mathematical formulations are required to assign thermal parameters for investigated heat exchanger.

Van Rooyen (2012) presented current status and future perspectives of modified Wilson plots and several works have been quoted, in which the modifications of the Wilson plot have been applied. The modified versions of original Wilson plot enabled developing correlations for both the inside and outside heat transfer coefficients (Young, 1957) and the establishing of three parameters: constants C_c and C_h and an exponent in heat transfer coefficient correlation (Briggs, 1969). The prospects of determining two and more constants by applying second linear regression have been widely described in (Fernández-Seara, Uhía, Sieres et al., 2007).

Many of the existing modifications of the Wilson method are not restricted to individual considered cases and can be successfully applied to other types of heat exchangers and flow conditions.

3. Literature review concerning Wilson plot

The subject of application of the Wilson method to various problems related to convective heat transfer, have been undertaken by many researchers throughout the years. Therefore, a brief overview of selected literature concerning the Wilson method, which covers approximately the last 20 years, was presented below. Particular attention was paid on determination of heat transfer coefficient in mini-, microchannels and conventional size channels with the flow of nanofluid, refrigerants and standard working media.

As far as Wilson plot method is concerned, the works of Fernandez-Seara et al. provided valuable general knowledge referring to this research field. The state-of-the-art review of both the original and modified Wilson plot methods was presented by Fernández-Seara et al., (2007). The fundamentals of Wilson method have been described and its various alternations have been reported. An experimental setup, which enabled the application of the Wilson method in practise and therefore to obtain heat transfer coefficients, was shown by Fernández-Seara et al. (2005). The trial measurements have been conducted and the standard and modified Wilson methods have been employed. It was noticed that the results of heat transfer coefficient obtained experimentally and determined from correlations were consistent. Then, Fernández-Seara, Uhía, & Sieres, (2007) proposed thermal characteristics of smooth and corrugated test tubes obtained by the Wilson method. The tubes have been experimentally investigated on the test stand presented by Fernández-Seara et al. (2005). Also results for both investigated configurations have been compared with standard correlations and satisfactory correspondence was achieved.

In the beginning of the XXI century, Wang et al. (1996) obtained heat transfer coefficients for microfin tubes by means of modified Wilson plot technique. The experiments were performed for several tube geometry inserted in a double-pipe heat exchanger with water as a working fluid. As a result, a general heat transfer correlation equation was suggested and the analysis concerning the selection of the appropriate correlation depending on the Reynolds number range, was presented.

The Wilson plot method was also applied to minichannel aluminium heat exchanger, as reported in (Fernando et al., 2008) for the purpose of determining correlations for single-phase heat transfer coefficients. The investigated heat exchanger had a form of a multiport minichannel tube with square shaped parallel channels. It was found that experimentally obtained Nusselt number fit well with the Nusselt number predicted from correlation in transition flow regime. However, for the case of laminar flow none of the well-known correlation predicted the Nusselt number properly.

Koo et al. (2016) studied experimentally thermal and hydraulic characteristics of shell and helically coiled tube heat exchangers with two different tube types. Wilson plot method was used for obtaining the overall thermal resistance, which in investigated case was determined as a linear function of inverse Reynolds number to the power of m. The authors also provided a comparison of thermal and fouling characteristics between shell and helically coiled tube heat exchanger and brazed plate heat exchanger.

Baba et al. (2018) employed both original and modified Wilson methods to determine Nusselt number correlation for the case of water nanofluid flow inside double tube heat exchanger with longitudinal fins on internal side. The authors reported that applied Wilson method corresponded well with experimental data.

Convective heat transfer and flow characteristics in helical coil double pipe heat exchanger have been also presented by Sheeba et al., (2019). Wilson plot method was applied to determine heat transfer coefficients on both sides of the inner tube. Experimental measurements of heat exchanger have been supported by numerical investigations and satisfactory results correspondence has been obtained.

In original Wilson method it is assumed that one fluid flow is kept constant, while the other is changed. Rybiński et al. (2018) developed such a modification of Wilson method, where both flows and temperatures may be modified at the same time. The presented method was applied to minichannel heat exchanger in order to obtain its thermal characteristics, which were determined statistically. Experimental measurements have been conducted as well. The new method is based on the determination of regression function of corrected overall thermal resistance, which statistically estimates the experimental overall thermal resistance with the use of linear correction coefficients. It was stated that the method can be successfully applied to other types of heat exchangers.

Another crucial aspect connected to the Wilson plot method is the uncertainty of experimental measurements. According to Rose (2004), theoretical considerations affecting the accuracy of temperature measurements in terms of applicability and usefulness of Wilson plot technique has been conducted. The author has also specified other certain factors essential for validity and accuracy of results obtained.

The uncertainty analysis applied to the results obtained by the Wilson plot method for the case of vapour condensation on horizontal plain tubes has been studied by Uhia et al. (2013). The general uncertainty propagation equation has been used. It was noticed that the influence of uncertainty of water temperature measurement on the experimental heat transfer coefficient obtained by the Wilson plot method was supreme and slight impact of uncertainty of flow rate measurements and vapour temperature has been observed.

The collective specification of abovementioned references is shown in Table 1.

Table 1. Summary of a brief overview of selected literature concerning the Wilson method

Reference	**Subject of study**	**Type of investigated heat exchanger**	**Conclusions**
(Fernández-Seara, Uhía, Sieres, et al., 2007)	Review of the original and modified Wilson plot methods	-	Wide range of application of the Wilson method, the method can be used to analyse various convective heat transfer problems
(Fernández-Seara et al., 2005)	The presentation of an experimental setup for the application of the Wilson method in practise	Smooth tube and a spirally corrugated tube	The consistency of results of heat transfer coefficient obtained experimentally and determined from correlations
(Wang et al., 1996)	Single-phase heat transfer and pressure drop characteristics	Microfin tubes inserted in a double-pipe heat exchanger	A suggestion of general heat transfer correlation equation depending on the range of Reynolds number

Table 1. *Cont.*

(Fernando et al., 2008)	Determining correlations for single-phase heat transfer coefficients	Multiport minichannel aluminium heat exchanger	In transition flow regime experimentally obtained Nusselt number matched the predicted Nusselt number and for laminar flow compliance was not achieved
(Kyoungmin Koo, 2016)	The studies of experimental thermal and hydraulic characteristics with the use of Wilson plot to obtain overall thermal resistance	Shell and helically coiled tube heat exchangers with two different tube types	The comparison of thermal and fouling characteristics between shell and helically coiled tube heat exchanger and brazed plate heat exchanger
(Baba et al., 2018)	The determination of Nusselt number correlations with the use of original and modified Wilson methods	Double tube heat exchanger with longitudinal fins with water nanofluid flow	Applied Wilson method corresponded well with experimental data
(Sheeba et al., 2019)	Convective heat transfer with the use of Wilson	Helical coil double pipe heat exchanger	Satisfactory correspondence of experimental

	plot and flow characteristics		and numerical results has been achieved
(Rybiński W., 2018)	The development of new modification of the Wilson method to statistically obtain thermal characteristics of heat exchangers	Minichannel heat exchanger	The determination of regression function of corrected overall thermal resistance with the use of linear correction coefficients
(Rose, 2004)	Theoretical considerations affecting the accuracy of temperature measurements in terms of applicability of Wilson method	-	The specifications of determinants essential for validity and accuracy of results in terms of heat transfer measurements
(Uhia et al., 2013)	The uncertainty analysis applied to the results obtained by the Wilson plot method	Horizontal plain tubes	Influence of uncertainty of water temperature measurement, of flow rate measurements and vapour temperature on the experimental heat transfer coefficient

4. Summary

This paper attempted to discuss the application capabilities of the Wilson plot method. The main concept of the original Wilson method has been presented and brief discussion of literature concerning Wilson plot method has been performed. For the purpose of the review featured in this paper, the most scientifically meaningful literature has been encapsulated, which referred to the last 20 years.

Wilson plot method is an outstanding calculation procedure of convective heat transfer coefficients, which constitutes a great potential of applicability in the context of heat exchangers and convective heat transfer in general. From the presented review it can be seen that Wilson method can be applied to both conventional and mini- and microchannel heat exchangers, where both the standard working media are used, as well as nanofluids and refrigerants, what proofs the versatility of the Wilson method. Despite that Wilson plot in its original form was developed over a century ago, it is still a valuable technique used to analyse heat transfer behaviour in simple heat exchanger configurations, both on the industrial and laboratory range. In addition, the modified versions of the Wilson method exceeded its applicability and overcome limitations imposed by primary method.

The greatest benefit of the Wilson technique is its simplicity and usefulness, especially when the temperature inside heat exchanger is impossible to determine, like in minichannel heat exchangers and microtubes. The method can be successfully adapted to almost every considered case with satisfactory accuracy. Due to the fact that there are a lot of modifications of the Wilson method and new ones keep appearing progressively, it is possible to obtain a dataset of results obtained by this method for the variety of individual cases. The additional potential of the Wilson method lies in the possibility of developing a correlation equation for investigated heat transfer condition, which can be validated by well-known correlations described in literature.

The main disadvantage of the Wilson method is its susceptibility for temperature measurement errors, which implies that even for minor measurement errors, negative values of heat transfer coefficients can be obtained. Another inconvenience pertains to the assumption of keeping one flow constant during one series of measurements, however after so many modifications, this assumption can be withdrawn.

The convergence between experimental data trend and correlation equation used is main determinant of assessing Wilson method accuracy. Certainly, the efforts should be made to ensure that this match is as good as possible, what could be the subject of interest for future researchers.

Taking into account the abovementioned considerations and susceptibility of the Wilson method to various modifications, it can be concluded that Wilson technique belongs to the group of evolutionary research methods with exceedingly broad development prospectives.

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ZASTOSOWANIE METODY WILSONA W ZAGADNIENIACH KONWEKCYJNEJ WYMIANY CIEPŁA – OMÓWIENIE

Streszczenie

W artykule omówiono i przedstawiono zastosowanie metody Wilsona w różnorodnych zagadnieniach związanych z wymianą ciepła na drodze konwekcji. Metoda Wilsona pozwala na analizę i określenie konwekcyjnego współczynnika przejmowania ciepła na podstawie eksperymentalnych pomiarów parametrów cieplnych i przepływowych badanego wymiennika ciepła oraz zastosowanie lub opracowanie odpowiednich zależności korelacyjnych. Szczególnym atutem metody Wilsona jest możliwość określenia współczynnika przejmowania ciepła bez konieczności pomiaru temperatury powierzchni badanego wymiennika ciepła Dużo uwagi poświęcono wyjaśnieniu koncepcji standardowej, oryginalnej metody Wilsona oraz jej zmodyfikowanych wersji. Zagadnienie zostało przedstawione w formie przeglądu literatury, w którym uwzględniono podsumowanie wyników badań współczynników przejmowania ciepła uzyskanych metodą Wilsona w następujących przypadkach: przepływu nanocieczy, czynników chłodniczych i innych mediów roboczych w kanałach konwencjonalnych i mini/mikrokanałach oraz mikrorurkach, jak również wymianę ciepła podczas wrzenia/kondensacji. Przedstawiono zasadność wykorzystania metody oraz określono jej perspektywy na przyszłość.

Słowa kluczowe: metoda Wilsona, wymiana ciepła, charakterystyka cieplna, wymiennik ciepła

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