Writing a Scientific Paper: From Clutter to Clarity

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Abstract

Preparing a manuscript is a time-intensive activity: organizing the technical content, preparing graphs and tables, writing, proofreading, and correcting syntax. Wordiness is a major impediment to communication: this document advocates writing concisely. We identify best practices for preparing graphs and tables. Together with conventions for significant figures, we tabulate typical grammatical errors and extraneous expressions. Write your paper well so that reviewers concentrate on the content.

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1. Introduction

A poorly written paper frustrates reviewers and risks rejection. The abstract is the first indicator that the manuscript will be hard-to-read. Symptoms include incorrect grammar, a lack of substantive results, erroneus units, grocery lists of equipment and modeling techniques, and jargon. A good abstract is short, grammatically correct and highlights the important results. Tips for writing are available on the internet and in books [1], [2]. Even textbooks [3] discuss writing practice and the philosophy of preparing documents and reports. Peters et al. [4] outline common errors related to personal pronouns, verb tenses, diction, and dangling modifiers. We go beyond describing the sections of a scientific paper. We list extraneous parenthetical expressions and verbs and illustrate, with examples, how to correctly express significant figures. We give precise dimensions for graphs that can be reproduced directly in a journal paper. Finally, for each section of the manuscript, we discuss the necessary content and advocate letting the experimental data tell the story.

2. Grammar

A well-written document gets to the point *(quickly, efficiently, and free of superfluous words)*. Avoid meaningless parenthetical phrases, adverbs and adjectives. Keep the language simple. Verb mutilation is one of the major causes of wordiness [5].

2.1. Verbs

The verb *to do* and particularly the participle *done* are prime examples of verbiage. For example, phrases like *experiments were done*, or *the measurement was done* shift the focus away from the data. *At* 50 °C *the solvent evaporated* is preferable to *the measurement was made at* 50 °C... The following sentence: *When using the infrared camera, the calibration was done between* −20 °C *to* 120 °C is better expressed by removing the participle *done*: *The infrared camera was calibrated between* −20 °C *to* 120 °C.

Try, use, perform and *make* are other verbs that often hide the active verb. For example, rather than stating *a needle valve was used to regulate pressure*, write *a needle valve regulated pressure*. The action worth mentioning is regulating pressure, not using a needle valve.

Table 1: Problematic Verbs

Verb	**Weak Phrase**
Do (done)	*The experiment was done at atmospheric pressure*
Try (tried)	*We tried an experiment at atmospheric pressure*
Use (used)	*A transducer was used to measure pressure*
Perform (performed)	*They performed experiments at high pressure*
Make (made)	*They made the experiments at high pressure*

Sentences in Table 1 are improved by eliminating the participle (on the left) and the irrelevant words such as *experiment* and *measure*. *Experiment* shifts the focus from the phenomenon in question to what was *done* or how it was *done*. When the sentence is properly constructed, the message becomes explicit: *The thermodynamic equilibrium favors the products at atmospheric pressure compared to high pressure.*

2.2. Expressions to Avoid

If you can delete a parenthetical expression at the beginning of a sentence without changing the meaning, it is extraneous. Avoid expressions such as *as can be seen from the figure* even though many top journals accept this construction. The journal *Nature* describes the information in the figure and cites the figure number in parentheses following the sentence (Fig. 1). Other expressions to avoid are:

- *It is shown that*
- *It can be noticed that*
- *It has to be mentioned that*
- *It should however be noted that*
- *It is clear that*
- *Regarding this fact that*
- *Is given by the fact*
- *Based on our experiments, understanding*
- *As can be seen from the figure (table)*
- *It takes into account the fact that*
- *It is identified that*

Sentences including words such as *however, moreover, nevertheless*, etc., are acceptable when used sparingly.

2.3. Quantitative vs. Qualitative

In a recent article sent for review, the author wrote *huge* five times in the first page of the printed manuscript. How much is huge? Is the author's huge the same as everyone else's? Under certain circumstances, huge may be as little as 1 %. Quantitative values are preferable. Rephrase sentences containing the adverbs in Table 2.

Be specific — instead of stating that samples were withdrawn often, cite the frequency. Be quantitative: *rates double* is better than *rates increase a lot*, or *significantly.* Adjectives are appropriate when they have been defined. A parenthetical expression may follow a quantitative statement to emphasize the authors' perception of the phenomenon: the rate doubles for every increase in 10 °C, *which is significant.*

Adverbs like *approximately*, *about*, and *around* express uncertainty but should be dropped if the uncertainty is already expressed or if the numerical value is stated with two or more significant figures. Change *The pump costs around 103 k$* to either *The pump costs 103 k$* or *The pump costs around 100 k$* In some patents, the words *about*, *approximately* and *around* are explicity defined to represent an uncertainty of ±5% to ±10%.

Table 2: Problematic Adverbs

Adverb	**Imprecise**	**Clear**
extremely	*the rate is extremely dependent on operating temperature*	*the rate depends on temperature*
significantly	*the rate increases significantly with temperature*	*the rate doubles for every increase in* 10 °C
very, a lot	*samples were withrawn from the tube very often*	*samples were withdrawn at a frequency of* $2\,h^{-1}$
approximately	*the test lasted approximately between* 5 s to 30 s	*the test lasted between* 5 s to 30 s

Be careful to correctly assign the adjective with the physical quantity, height, value, time, etc. (Table 3).

Table 3: Adjectives and their Properties

Adjective	**Property**
bigger, larger	physical size
higher	height, position
greater	quantity, value
longer	time, length

Avoid the word *works* except for the third-person singular. When referring to previous studies, articles, or work, *works* is unacceptable.

Use the word *not* sparingly. Texts are easier to read and assimilate when they are structured in the positive tense. Use prefixes when possible (Table 4): *insensitive* is better than *not sensitive*. Adjectives are often included for emphasis, which is unwarranted. Thus, *not sensitive enough* should just read *insensitive*. Also, be careful with expressions like *show high similarity*. Write instead *are similar*.

Table 4: Negative Prefixes

Not accurate	Inaccurate	Not correct	Incorrect
Not complete	Incomplete	Not favourable	Unfavourable
Not sensitive	Insensitive	Not sufficient	Insufficient
Not necessary	Unnecessary		

2.4. Wordy

Reducing the number of words in a document results in a text that is direct and readable. In the phrase *show high similarity* the verb *to be* is substituted by the verb *to show*. As a consequence, the adjective *similar* is replaced by the noun *similarity*. Wordy texts transform adjectives to nouns and hide the active verbs. Below, we list poorly constructed sentences and their improved counterparts.

- *It has been found that CO_2 and H_2O formation has been reduced at high temperatures.*

  This sentence's first deficiency is the parenthetical expression *It has been found that*. It can be removed without changing the sentence. Secondly, *has been reduced* can be replaced and the sentence becomes:

  CO_2 and H_2O formation is lower at higher temperatures.

  The sentence may be further improved by recognizing that the verb *to form* is hidden in the noun *formation*.

  Less CO_2 and H_2O was formed at higher temperature.

- *Briefly, it is reported here that the preparation method has involved a solid liquid reaction between an n-hexane solution of small Rh clusters and the powdered oxides (Al_2O_3, MgO and CeO_2).*

  As with the previous example, this sentence contains the unnecessary phrase *Briefly, it is reported here*. Also the verb *to prepare* has been converted to the noun *preparation*. Small — an unspecified quantity — is replaced with a specific quantity: 100 nm. Thirteen words are removed from the sentence.

  The powder was prepared by reacting 100 nm *Rh clusters and Al_2O_3, MgO and CeO_2 powder in n-hexane.*

- *Conversion over* 90 % *was achieved with a residence time of 20 minutes.*

  The number of words (and characters) is reduced by a factor of 2 by using the active voice: substituting *were achieved* with *exceeded*.

  Conversion exceeded 90 % in 20 min.

- *Coal pyrolysis to acetylene is carried out under ultra high temperature and milliseconds residence time.*

What is the demarcation between *high temperature* and *ultra high temperature*? How much time does *milliseconds* represent? Why let the reader guess? Be specific. Be brief. Use verbs.

Coal pyrolyses to acetylene in 10 ms *above* 1500 °C.

- *Figure 1 shows the relationship between butane conversion and yield as a function of butane and oxygen concentrations.*

  Referencing tables and figures in the body of the manuscript is a matter of taste. The journal *Science* allows the above contruction but *Nature* rejects it. Rather than wasting space stating the obvious, describe the relationship between yield and conversion as a function of composition. Describing the figure could take several sentences but the first sentence can be more specific.

  MA yield increases linearly with conversion regardless of butane or oxygen mole fraction (Fig. 1).

- *The catalyst is characterised using BET, mercury intrusion porosimetry, Raman spectroscopy, thermogravimetric analysis, and density measurements, before and after* 500 h *of on stream operation.*

  Avoid a grocery list of techniques like the sentence above. In the abstract, cite the results:

  After 500 h *on stream, the surface area dropped from* $71\,\mathrm{m^2\,g^{-1}}$ *to* $5\,\mathrm{m^2\,g^{-1}}$ *and the porosity declined* 15 %, ...

- *... as already extensively documented [*ref_1*,* ref_2*].*

  ...[ref_1*,* ref_2*].*

- *... was demonstrated to be excellent*

  was excellent

- *... must be kept to a minimum*

  must be minimized

  The passive voice here can often be converted to the active voice using the imperative:

  minimize

- *found to be able to account for*
  accounted for
- *at three levels of temperature*
  at three temperatures
  or, better yet
  at 360 °C, 380 °C *and* 400 °C
  Other expressions to avoid:
- *best results were obtained...*
- *The use of the model and experimental results lead to four main conclusions.*
- *In this study, a set of experiments in an original set-up and with a new data treament procedure is presented*
- *... additional experimentation was completed.*
- *Considerable effort has been applied in order to gain an understanding*
- *The comparison of simulation and experimental results validates the model.*

3. Reporting data

Eighteen out of twenty articles published in a journal with an impact factor (IF) greater than 2.2 reported data poorly. Errors included carrying too many significant figures and poor choice of units. Experimental data is imprecise. Temporal and spatial variations in reactors are greater than 10 °C (and as much as 100 °C). Reporting temperature to five significant figures is unwarranted. Cost data is often unrealistically reported to within 1 $. Fitted parameters to calculate thermodynamic properties (C_p, for example) are reported with seven significant figures or more. Atmospheric pressure is stated as 101 325 Pa but barometric pressure varies by as much as 5000 Pa in a single week. Derived variables such as conversion and selectivity depend on flow rates, species concentration, pressure and temperature, each of which has a certain level of uncertainty. The target on closing a mass balance around a reactor is 5 %: reporting conversion with three significant figures overstates the certainty.

If the standard deviation of a measurement is ±2 %, how many measurements are required to justify carrying three significant figures? Standard deviation, error and uncertainty are often confused. Error is the difference between the measured (reported) value and the true value as established by a recognized standard. There are random errors, systematic errors and blunders [6]. Random errors are characterized with statistical methods. Systematic errors are corrected through calibration, modifying procedures, etc. Standard deviation is the square root of the variance and characterizes the random error around the mean of a population of data. The uncertainty (also known as the margin of error), Δ, refers to a range of values in which the true value is likely to be found. It is expressed as the product of the standard deviation, σ, and a confidence interval, $k(\alpha)$, where the level of confidence, α, is often assumed to be 95 %.

$$\Delta = k(\alpha) \cdot \sigma \tag{1}$$

The confidence interval equals 1.96 (≈ 2) for a 95 % level of confidence for a normally distributed population of data. Therefore, any single measured value has a 95 % likelihood of lying within $\pm 2\sigma$.

The uncertainty is lower when multiple experiments are made and the results are averaged. It equals the product of the t-value of the Student's t-statistic and the sample standard deviation, s, divided by the square root of the number of repeats, n (degrees of freedom):

$$\Delta = t(\alpha, n-1) \cdot s/\sqrt{n} \tag{2}$$

How many repeats are required to justify carrying three significant figures? Assume the sample standard deviation of 30 measurements equals 2 % (so, $t(\alpha, n-1) \approx 2$). The number of experiments required to carry the third significant figure to an uncertainty of ±0.005% becomes

$$n = [t(\alpha, n-1) \cdot s/\Delta)]^2 = [2 \cdot 0.02/0.005]^2 = 64 \tag{3}$$

Conducting 64 tests is prohibitive and a precision of three significant figures is excessive. Note that to reduce the level of uncertainty to ±0.001%, 1600 repeat experiments would be required.

As an exercise in expressing data, improve the following expressions:

1. $d_p = 2.5 \times 10^{-6}\,\mathrm{m}$
2. $T = 793.15\,\mathrm{K}$
3. 3962 \$/metric ton
4. $\mathrm{Q} = 1.46 \times 10^3\,\mathrm{m^3\,s^{-1}}$
5. $\sigma_Q = 6.9 \times 10^2\,\mathrm{m^3\,s^{-1}}$
6. $\Delta H_f = -1501.660\,\mathrm{kJ\,mol^{-1}}$
7. $Ea = 50.208\,\mathrm{kJ\,mol^{-1}} \pm 0.053$
8. Ash content = 12.34 %
9. An estimate of 0.693
10. An increase of 39 % and 35.6 %
11. Identify all of the expressions that are acceptable
    (a) 7.928 ± 0.0495
    (b) 7.928 ± 0.049
    (c) 7.928 ± 0.05
    (d) 7.93 ± 0.05
12. The following correlation is accurate to within 3.2 %

$$S_r = 2.12(1 + 0.279S)^{0.156} St^{0.0755} Re^{0.377} \qquad (4)$$

The expressions above were taken from the same journal (with an IF>2.2). Most of them could be improved by expressing the uncertainty with fewer significant figures or as a percentage. Item 11(d) would become $7.93 \pm 0.6\,\%$. (Note that the units corresponding to 7.93 are absent.)

4. Graphs

Graphs are an effective means to communicate data. Make graphs instead of tables. However, when the trends are simple (straight lines, three data points or less), cite the data within the text of the document: *Increasing the temperature from* 120 °C *to* 140 °C *doubled the reaction rate.* When discussing graphs, highlight trends and discuss their significance with respect to expectations. Avoid sentences that give no information other than directing the reader to the figure or table, for example: *Figure 1 shows the summary results of the TGA analysis.*

The principal elements of a graph are axes, number of ticks, tick labels, axes' titles, symbols for experimental data, lines (for trends or models), grid lines, legends, symbol size, line thickness and colours.

4.1. Axes

Choose the axes so that the experimental data extends to its limits. Often, the axes begin at (0,0). However, if the data ranges are distant from (0,0), then the minimum and maximum values of the axes should correspond to those of the data. For data that varies logarithmically, begin the origin at the lowest exponential value near the minimum. Place the origin at 10 for values ranging from 10 to 100; place it at 1000 when the minimum value lies between 1000 to 10 000, etc. Exclude grid lines except for log-log plots (perhaps). Graphs help the reader understand significant trends. Extraneous lines add clutter. Readers can extract precise values from PDF graphs with computer discretization technology.

The maximum number of major ticks on a graph should be about 5 (excluding the origin). The maximum number of minor ticks should not exceed 10. Often, minor ticks are unnecessary.

4.2. Data

Reserve symbols for experimental data and lines for models and correlations. Many authors include lines to help the reader follow the trends in the data. This practice is discouraged. Symbols should include error bars. However, the size of the symbol may also be chosen to represent the error. When the graph contains several sets of data, each set should have its own colour and symbol type (circle, square, diamond, etc.). Colours are useful even when the article is printed in black and white because it results in different shades of gray. Moreover, articles are increasingly available on the internet in colour.

4.3. Text

Minimize the text in graphs. Instead of writing *Temperature* (°C) as an axis title, write T, °C. This recommendation applies to legends as well as tick labels. Report the tick label as 2 µm instead of 2×10^{-6} m. A recent article wrote the following for the text in the legend: *Temperature profile from simulation with cooling temperature* 690 °C. This is an extreme example. Obviously *Temperature profile* is extraneous since the plot was temperature versus time. The word *simulation* is unnecessary when following the norm that data are expressed as symbols and models are expressed as lines. *Temperature* should be abbreviated and *cooling* could be subscripted: $T_{cooling} = 690\,°\mathrm{C}$.

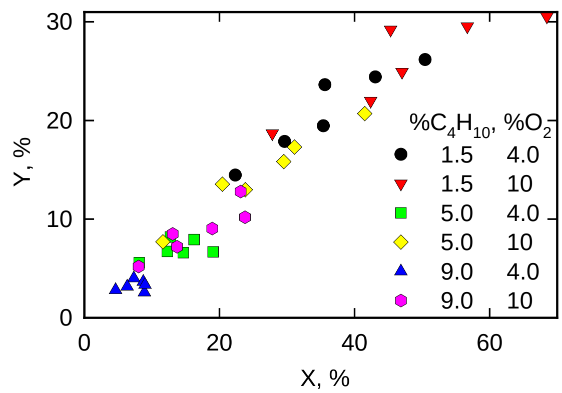

Figure 1: MA Yield v. Butane Conversion

4.4. Format

Figure 1 illustrates a graph that minimizes text while maximizing information. It respects the guidelines discussed above and is also easily embedded in the body of the text. Respect the following geometrical and configurational criteria in order to facilitate preparing graphs that are ready for publication. Some of the recommendations are cosmetic while others are critical to making a scalable graph.

Figure 1 was prepared in Sigmaplot®. The frame is 85 mm wide by 55 mm high. The text is 12 pt Arial for legends, tick labels and axes' titles. The legend is reported within the graph and is organized in columns to eliminate the necessity of repeating $\%C_4H_{10}$ and $\%O_2$. The symbol type and color are unique for each data set. Different shades of gray result when the graph is printed in black and white. The symbol size is 2.6 mm with a 0.1 mm thick black contour line. The line thickness of the axes is 0.4 mm. Major ticks point inward with a line thickness of 0.3 mm and a line length of 1.6 mm. Minor ticks are absent. When minor ticks are necessary, make them shorter (0.8 mm) and narrower (0.1 mm) than the major tick. When a graph contains multiple lines, distinguishing one line from another is difficult. In this case, place the text in the vicinity of the line instead of writing a legend.

5. Tables

As mentioned above, graphs are preferred to tables when presenting experimental data. Tables are appropriate for lists. Write explicit and informative titles. Avoid sentences. Column titles should contain the symbol name (abbreviate the titles — T instead of *Temp.* or *Temperature*). Include the units in the title instead of reporting the symbol unit after each value in the table. For large or small numbers, adopt the appropriate SI prefix. Most data warrant no more than three significant figures, or even two. Carrying more significant figures is only justified for a large number of experiments.

6. Preparing the Manuscript

When writing your manuscript for the first time, ignore the grammatical rules cited in this document! Write quickly and come back later to correct. When you start to write, do not stop to edit. Concentrate solely on writing; try a pen instead of a text editor/word processor. Typing can be slower because of the tendency to correct spelling mistakes and grammar while composing text. Collect your thoughts and structure your paper with mindmaps [7]. You can even write paragraphs with this technique.

- write
- correct
- type
- correct

6.1. Organize the data

Data is everything. Data talks, bullshit walks. Organize it to be clear and concise. Before organizing the data, list the tests that were made, decide what is important, and arrange the ideas in a logical order. During this step, check for consistency. Is it complete and coherent? Calculate the uncertainties. If the standard deviation is too large, repeat experiments. When the data set is complete (to your satisfaction), you must be critical and decide what is appropriate to report and what is unnecessary. Characterize the trends with physical phenomena. If the trends run counter to the phenomena, repeat tests to confirm the trends (and look for a alternative hypotheses).

6.2. Title

Try to catch the reader's attention with the title. It represents the subject, the objective and even the results. Limit it to 12 words or less than 100 characters; shorter is better. Avoid abbreviations (except for chemical symbols) as well as long strings of nouns and adjectives. Consider the following title: *Kinetics of mixed copper-iron based oxygen carriers for hydrogen production by chemical looping water splitting* [8]. It is long. It mentions the technology and the focus on kinetics with mixed metal oxide. The following title is much more powerful: *Cu-Fe mixed oxides split water.* It is intriguing and focuses on the result: splitting water.

6.3. Abstract

The abstract is arguably the most important part of a manuscript. Like the title, a short abstract is better. Summarize the major contributions such that the reader appreciates the significance of the work without reading the entire document. Focus on the results, not the means. We recommend writing the abstract several times: at the beginning (even before all the data is collected!), when the paper is nearly complete, and at the end to reflect the finished manuscript. Organizing and writing the abstract brings clarity. As with all writing, do it rapidly. The following sentence is an example of what not to do:

The effects of various design and operating parameters on the performance of the proposed reactor were investigated using a detailed model-based analysis.

This sentence is uniformative and conveys valueless information. What design and operating parameters were changed? What was the model? What was the effect? Two or three sentences are required to convey pertinent information.

Selectivity decreased by 20 % *while increasing temperature from* 700 °C *to* 1000 °C *at constant pressure. Selectivity increased by* 10 % *with increasing pressure from* 1 bar *to* 5 bar. *A redox kinetic model accounted for* 87 % *of the variance in the data.*

6.4. Introduction

The introduction delimits the scope of the work. General introductions allow readers to appreciate the importance of the subject. The first couple of paragraphs may include a historical context, or mention the economic incentive or the scientific interest. The problem can be described with possible solutions proposed by others. A critical review of the literature follows. The

novelty of the work comes next and includes the main objectives. Bear in mind what Joseph Pulitzer had to say about writing:
"Put it before them briefly so they will read it, clearly so they will appreciate it, picturesquely so they will remember it and, above all, accurately so they will be guided by its light."

6.4.1. Literature Review

Reviewing literature is a continuous activity. Mention the major contributions, any controversy and what is left to be done in this section. A critical review requires a couple of sentences for each reference to describe the salient features of the previous work and its limitations. When several articles touch on the same subject in a similar manner, they can be referenced simultaneously $[ref_x - ref_{x+y}]$. As many as 20 pertinent references is sufficient. Most scientific articles ignore patents and vice versa. In fact, patent literature can be an enormous source of inspiration.

6.5. Experimental Methods

Considering what Pulitzer said, the Experimental Methods and materials section must be stated concisely, clearly and accurately so that others may replicate the results. Include only professional images that demonstrate the experimental apparatus. Include schematic diagrams and describe major pieces of equipment individually as well as the experimental sequence chronologically. Describe the sampling procedure, if any. Use tables to summarize the experimental conditions. State the invariant factors in the body or in the captions to keep tables manageable.

List all materials and reagents as well as their purity. Indicate if the reagants were further purified or were synthesized as part of the study. Reference the synthesis steps where appropriate rather than repeating them. Provide the brand and the model of the analytical instruments as well as the conditions. Highlight data that helped design the experiments described in the results section.

6.6. Results and Discussion

This section constitutes the bulk of your paper. It substantiates what you say in the abstract and conclusions. Summarize the data in graphs and tables and discuss the obvious trends in the body of the text. Interpret the data. Include literature references to corroborate your results. If the results are inconsistent with literature, highlight the differences. Explain all your results and be critical.

6.7. Conclusions

People often read the conclusions directly after the abstract. Do not repeat the abstract. In fact, some journals skip the conclusions section. Avoid restating the problem and the context of the work but highlight the most significant findings. Consider mentioning the limitations of the work or issues that remain. Address the implications of the work in a context relevant to other systems, scale-up, and applications.

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Appendix A. Solution to exercises

$d_p = 2.5 \times 10^{-6}$m	$d_p = 2.5\,\mu$m
$T = 793.15\,$K	T=520 °C (Implied uncertainty ±10 °C)
3962 \$/metric ton	4000 \$/t
Q = 1.46×10^3 $m^3\,s^{-1}$	Q = 1460 $m^3\,s^{-1}$ $\pm x$ %
σ_Q = 6.9×10^2 $m^3\,s^{-1}$	σ_Q = 700 $m^3\,s^{-1}$
$\Delta H_f = -1501.660\,\mathrm{kJ\,mol^{-1}}$	$\Delta H_f = -1500\,\mathrm{kJ\,mol^{-1}} \pm x$ %
$Ea = 50.208\,\mathrm{kJ\,mol^{-1}} \pm 0.053$	$Ea = 50.2\,\mathrm{kJ\,mol^{-1}} \pm 0.1\,\mathrm{kJ\,mol^{-1}}$
An estimate of 0.693	An estimate of 0.7
An increase of 39 % and 35.6 %	An increase of 39 % and 36 %
Ash content = 12.34 %	Ash content = 12.3 % $\pm x$ %
7.93 ± 0.05	Missing units

For an equation with a 3.2 % error, three significant figures for the exponents is excessive:

$$S_r = 2.12(1 + 0.28S)^{0.16} St^{0.076} Re^{0.38} \tag{A.1}$$